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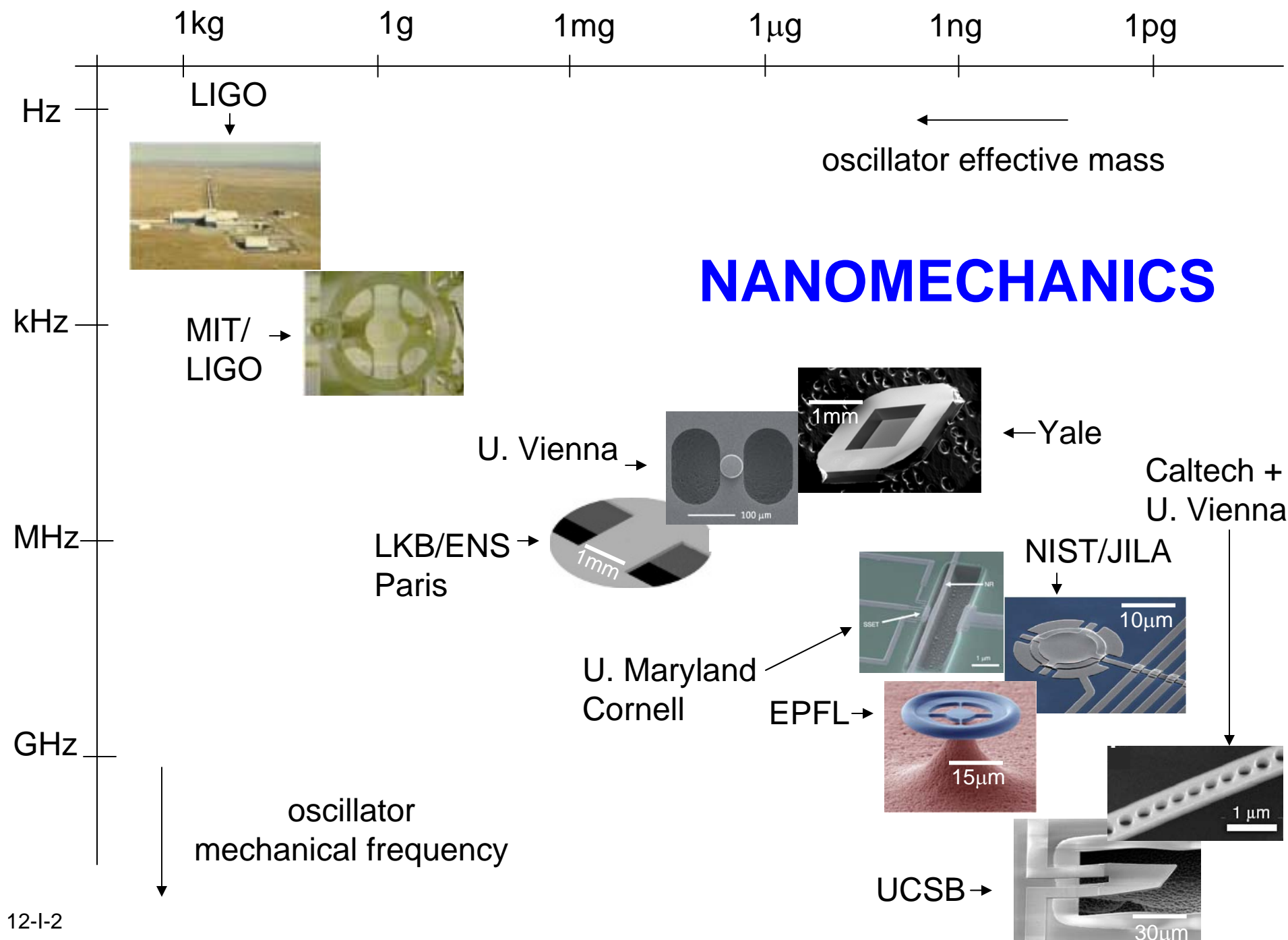
Chaire de Physique Mésoscopique  
Michel Devoret  
Année 2012, 15 mai -19 juin

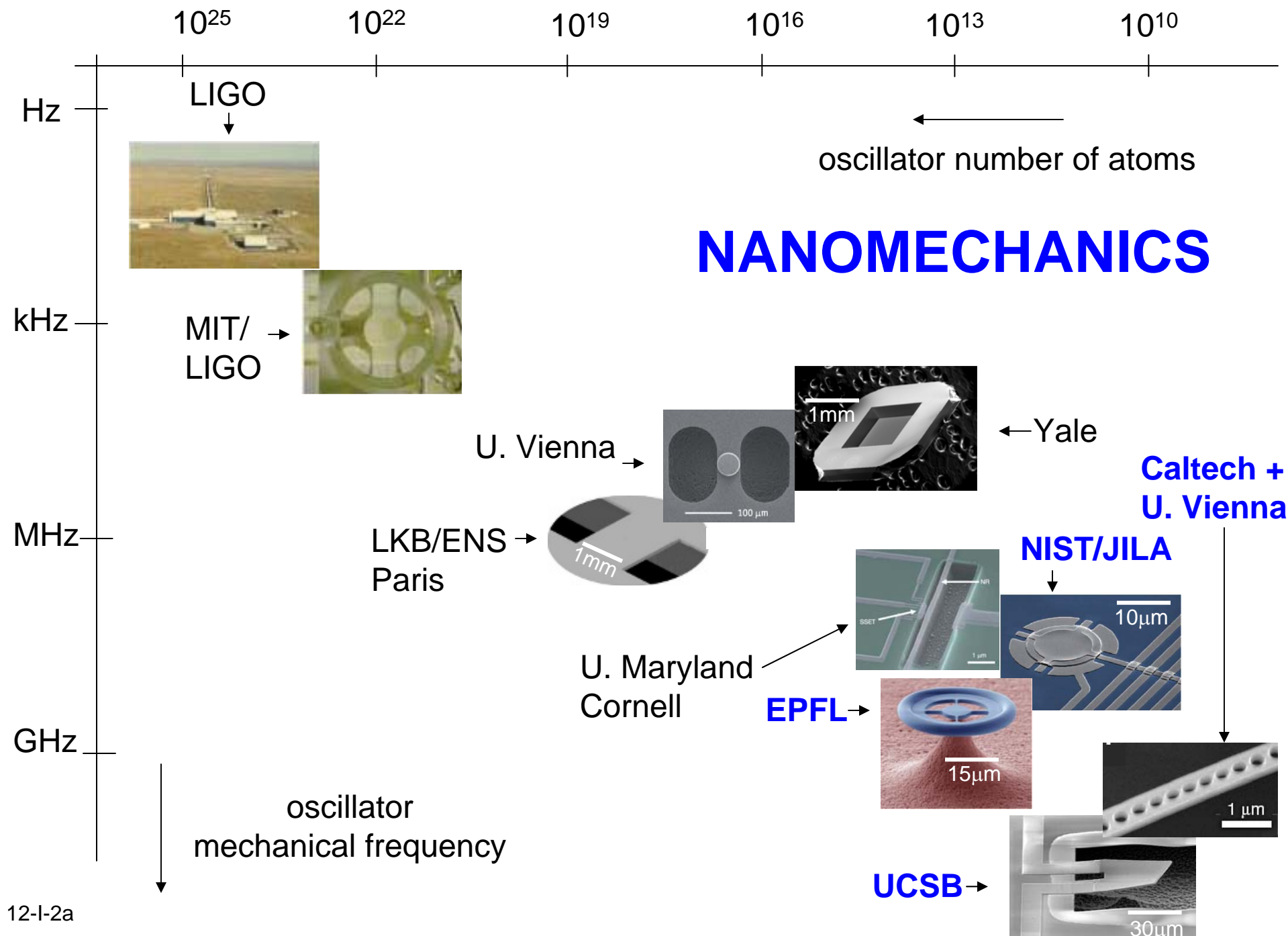
# RÉSONATEURS NANOMÉCANIQUES DANS LE RÉGIME QUANTIQUE

## *NANOMECHANICAL RESONATORS IN QUANTUM REGIME*

Première leçon / *First lecture*

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# LECTURE I : INTRODUCTION TO QUANTUM ELECTROMECHANICAL AND OPTOMECHANICAL ENGINEERED SYSTEMS

## CONTENTS

1. When do macroscopic object behave quantum mechanically?  
Macroscopic, engineered quantum harmonic oscillator as prototypical quantum machine
2. From the diatomic molecule to the macroscopic oscillator
3. Measuring the motion of a nanomechanical resonator
4. The problem of cooling a nanoresonator to its ground state
5. Three points of views on electro/opto-mechanics

# THE MACROSCOPIC MECHANICAL OSCILLATOR

Example: pendulum



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

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

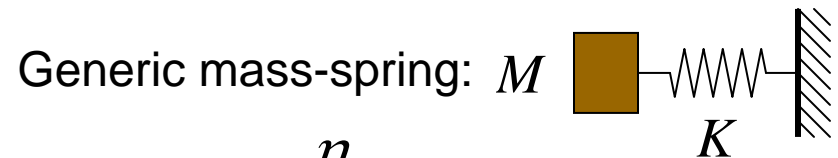
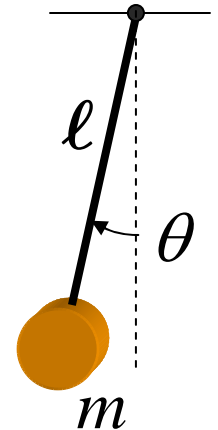
$$p_\theta = \frac{\partial \mathcal{L}}{\partial \dot{\theta}} = M \dot{\theta} \Rightarrow H = \frac{p_\theta^2}{2M} + K(1 - \cos \theta)$$

$$\dot{\theta} = \frac{\partial H}{\partial p_\theta} = \frac{p_\theta}{M}$$

$$\dot{p}_\theta = -\frac{\partial H}{\partial \theta} = -K \sin \theta$$

mechanical impedance

$$\omega_0 = \sqrt{\frac{K}{M}} = \sqrt{\frac{g}{\ell}}; \quad Z_0 = M \omega_0 = \sqrt{KM}$$



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

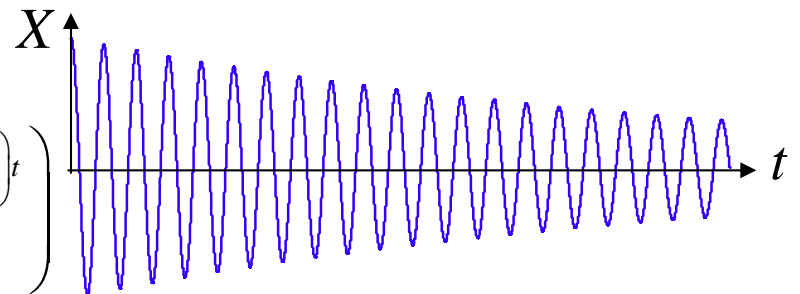
Damping quality factor:

$$Q = \frac{\omega_0}{\gamma} = \frac{Z_0}{\eta}$$

Underdamped regime:

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

(for  $F=0$ )



# QUANTUM TREATMENT OF MECHANICAL HARMONIC OSCILLATOR

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

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

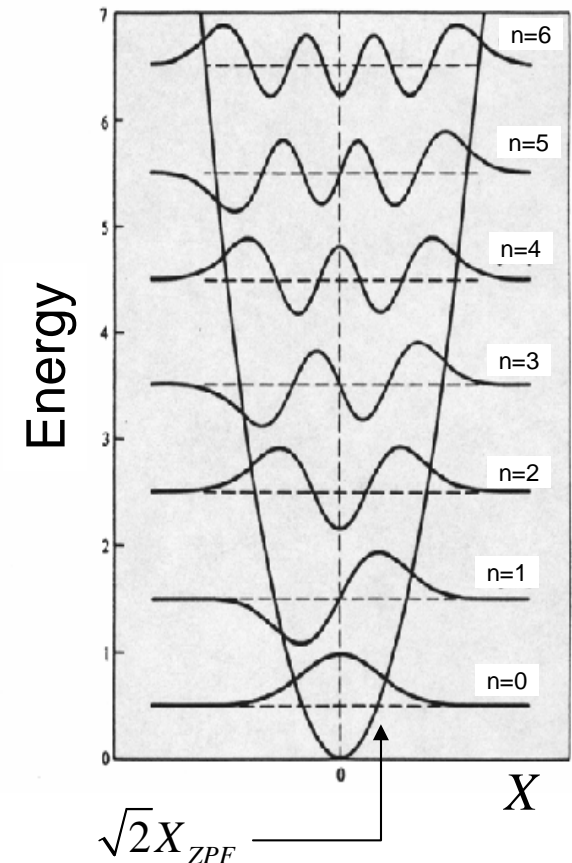
$$\hat{X} = X_{ZPF} (\hat{a} + \hat{a}^\dagger); \quad P = P_{ZPF} (\hat{a} - \hat{a}^\dagger) / i$$

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

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

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

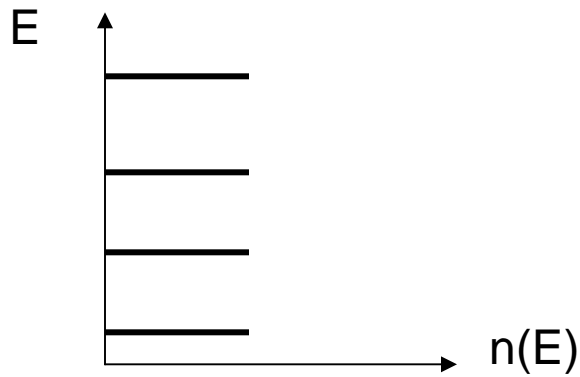
$$|\alpha\rangle = e^{-|\alpha|^2/2} \sum_n \frac{\alpha^n}{\sqrt{n!}} |n\rangle \quad \text{"Coherent" state}$$



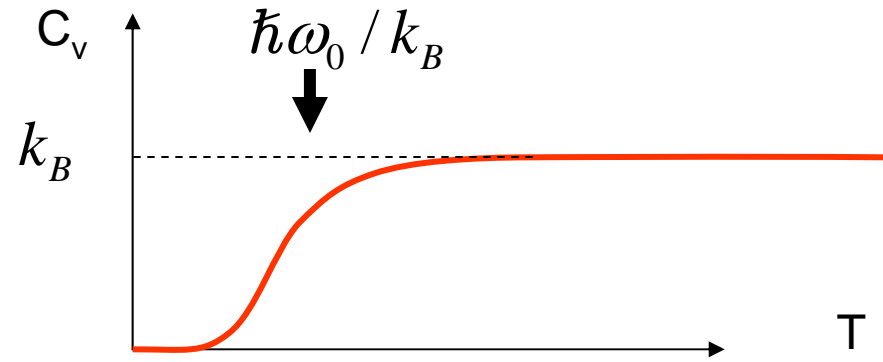
Can we observe the quantum behavior of a macroscopic oscillator?

# DIFFICULT REQUIREMENTS

12-I-6

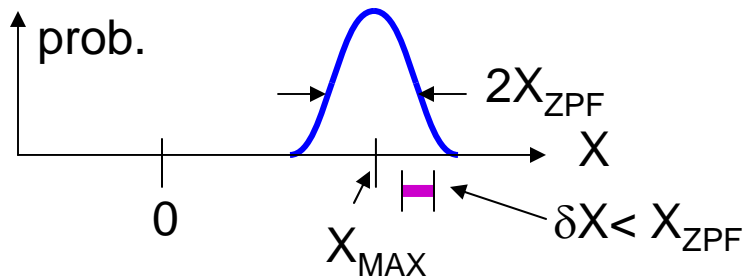


Discrete spectrum:  
must reach low excitation number



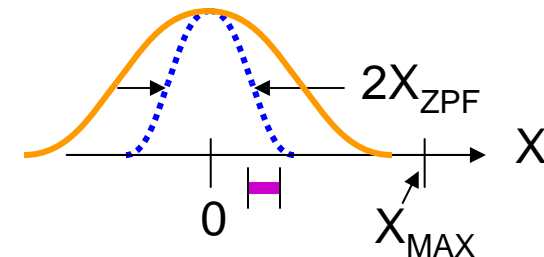
Vanishing specific heat at low T:  
need very sensitive calorimetry

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



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

THEN



$X$  is re-measured a quarter-period later, with same imprecision  $\delta X$ . 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  $5 \times 10^{15}$  Hz, with non-linearity of  $\sim 5\%$ . *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	$6.85 \times 10^{11}$
Double ended tuning fork	Single crystal Si	154 kHz	80,000	$1.23 \times 10^{10}$
Clamped-clamped beam	Single crystal Si	80 kHz	74,000	$5.92 \times 10^9$
Clamped-clamped beam	Poly-Si	9.34MHz	3,100	$2.90 \times 10^{10}$
Wine glass disk	Poly-Si	60MHz	145,780	$8.75 \times 10^{12}$
Wine glass disk	Single crystal Si	149.3MHz	45,742	$6.83 \times 10^{12}$
Radial-contour disk	Poly-Si	193MHz	23,000	$4.44 \times 10^{12}$
“Hollow-disk” ring	Poly-Si	1.2GHz	14,603	$1.75 \times 10^{13}$
Impedance-mismatched disk	Poly-diamond	498MHz	55,300	$2.75 \times 10^{13}$
Square extensional	Single crystal Si	2.18MHz	1,160,000	$2.53 \times 10^{12}$
Square Lamé	Single crystal Si	6.3MHz	1,600,000	$1.01 \times 10^{13}$
Length extensional	Single crystal Si	12MHz	180,000	$2.16 \times 10^{12}$
Convex quartz	Quartz	10MHz	1,300,000	$1.3 \times 10^{13}$
Wine glass disk	Single crystal Si	5.43MHz	1,900,000	$1.02 \times 10^{13}$

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

# MICROSCOPIC MECHANICAL HARMONIC OSCILLATOR

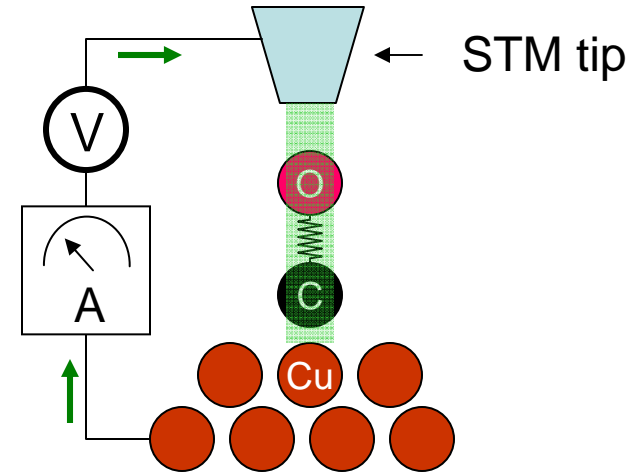
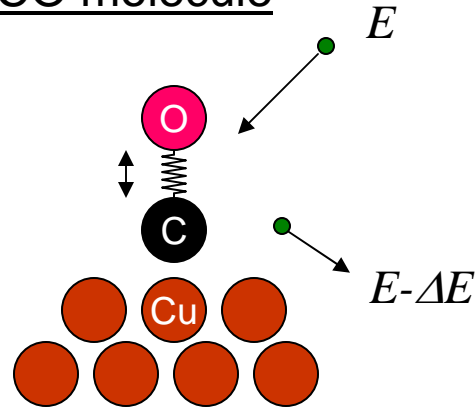
Example of CO molecule

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

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

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

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



HREELS

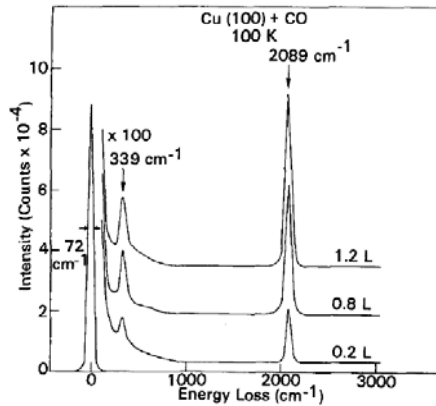


Fig. 7. Energy loss spectrum of CO adsorbed on Cu(100) at 100 K, at different coverages. The 1.2L spectrum is approximately 0.6 monolayers. The beam energy was 5eV

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

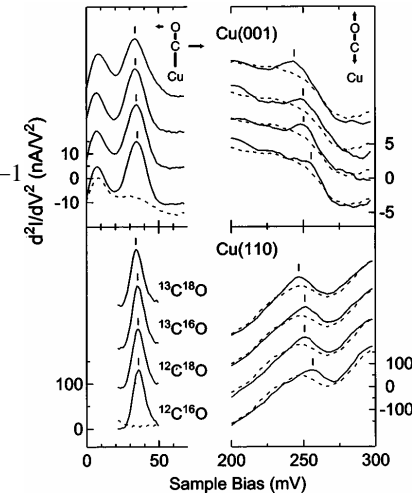
Appl. Phys. A 26, 1-18 (1981)

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

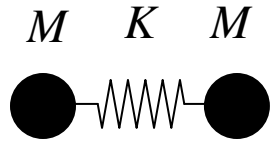
15 SEPTEMBER 1999-II

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

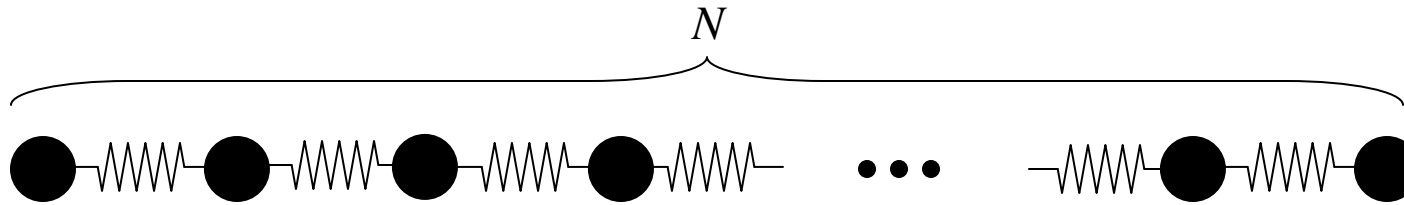
L. J. Lathou and W. Ho  
Laboratory of Atomic and Solid State Physics and Cornell Center for Materials Research, Cornell University, Ithaca, New York 14853  
(Received 6 May 1999)

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



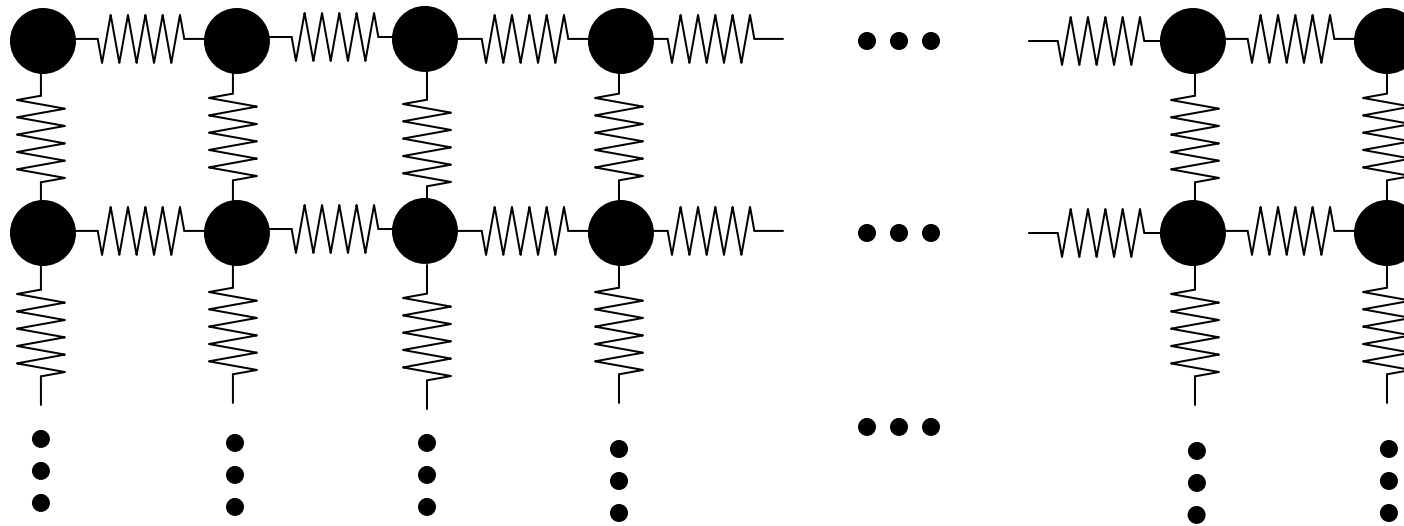
$$\omega_m = \sqrt{\frac{2K}{M}} = \sqrt{2}\omega_0$$



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

$$M_{eff} \approx NM$$

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

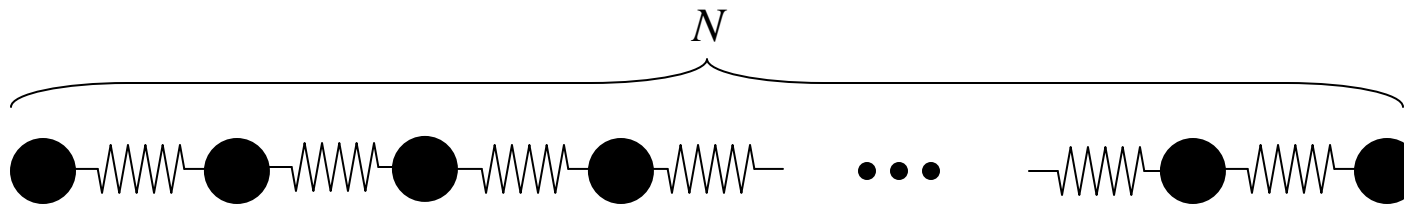
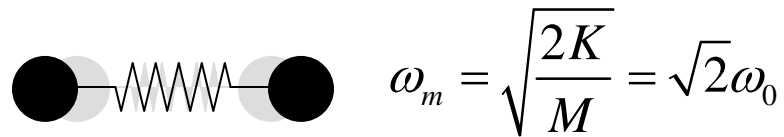
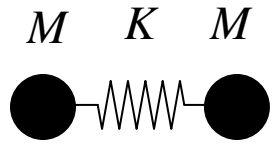


$$K_{eff} \approx N'K / N$$

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

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

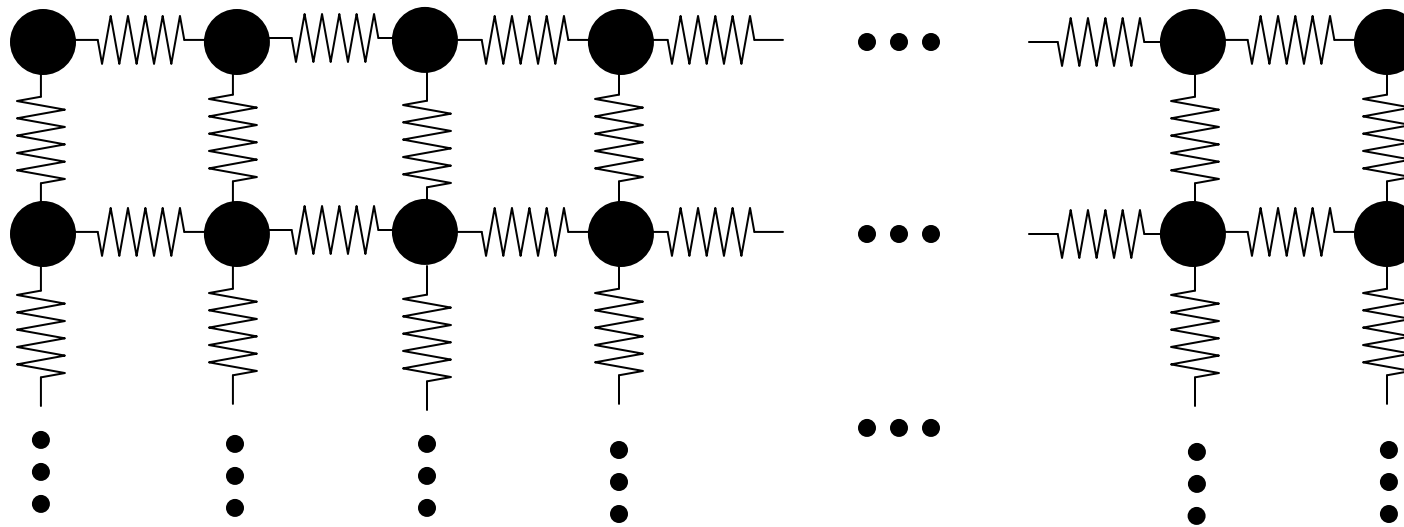
# FROM MOLECULES TO SOLIDS



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

$$M_{\text{eff}} \approx NM$$

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



$N'$

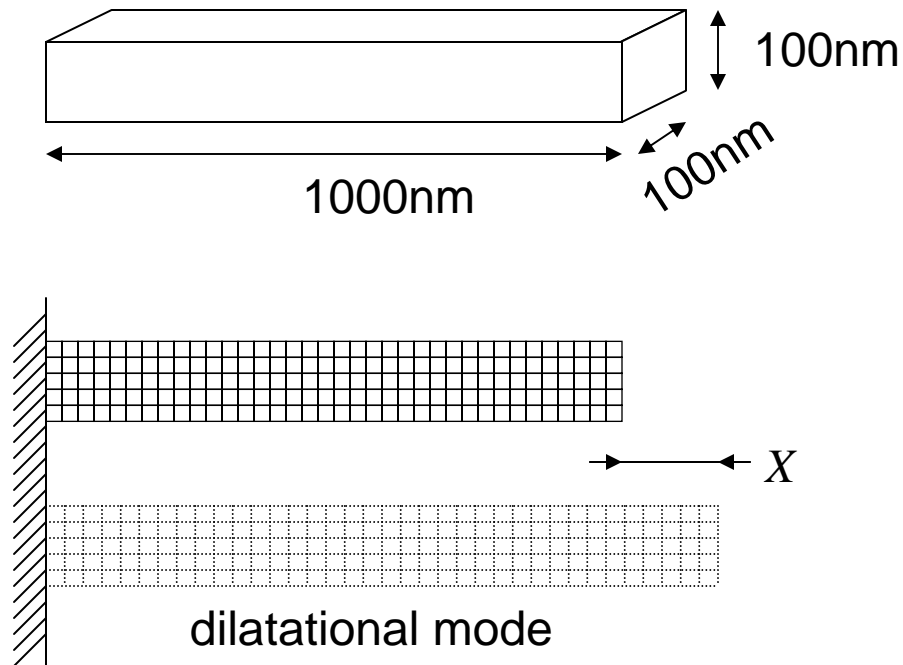
$$K_{\text{eff}} \approx N'K / N$$

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

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

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

# MOTION OF A NANOMECHANICAL BEAM



Flexural modes have lower frequencies and smaller mechanical impedances.

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

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

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

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

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

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

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

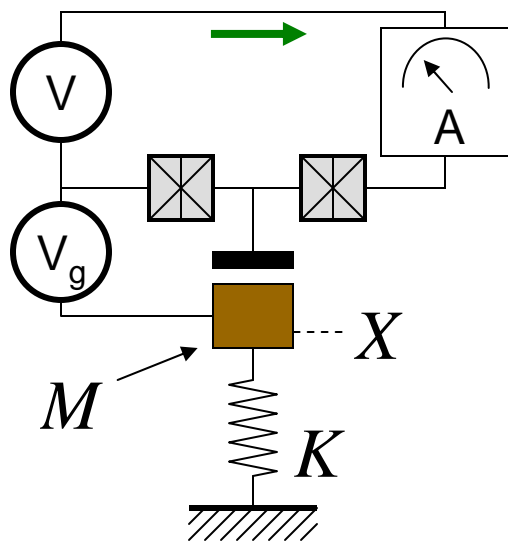
$$X_{ZPF} = 10^{-3} X_{ZPF,0} \approx \text{fm!}$$

# HOW CAN WE MEASURE OSCILLATOR POSITION?

## 3 main strategies

### Single Charge Transistor (or DC SQUID):

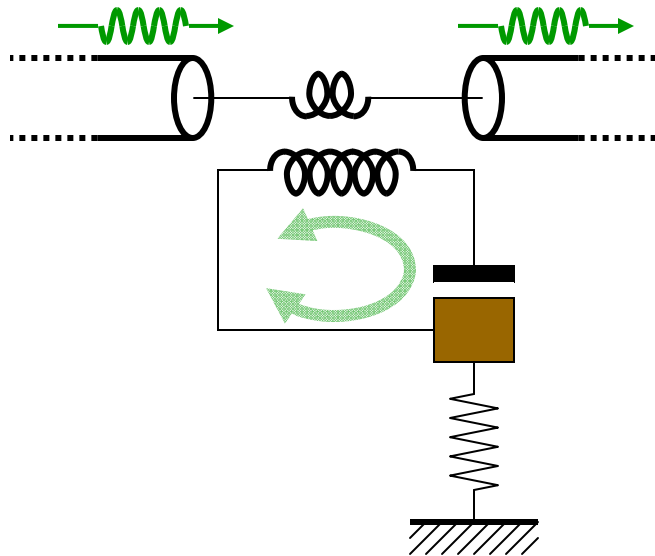
Charge induced on island gate capacitance by oscillator mass placed at elevated potential modulates current thru the device (in SQUID, flux modulates voltage)



NIST, U. Maryland, UCSB, Cornell

### Microwave resonator:

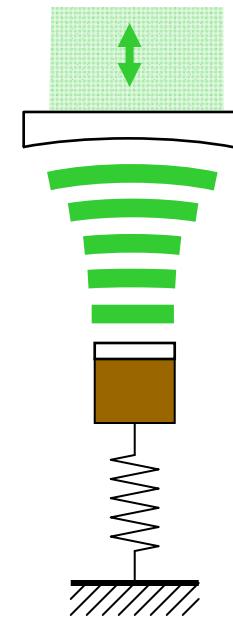
Resonator frequency modulated by displacement of oscillator mass. Phase shift of microwave signal coupled to the resonator carries information about mass position



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

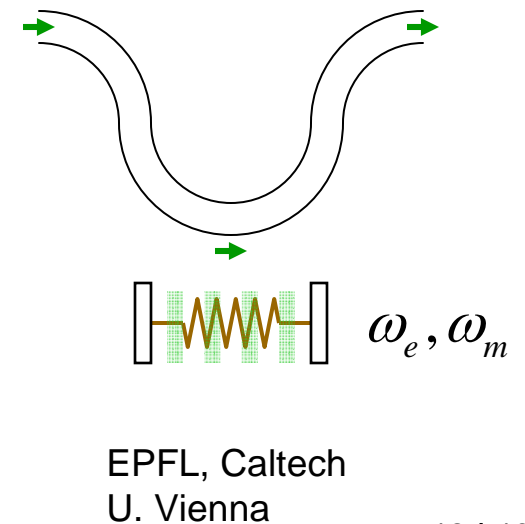
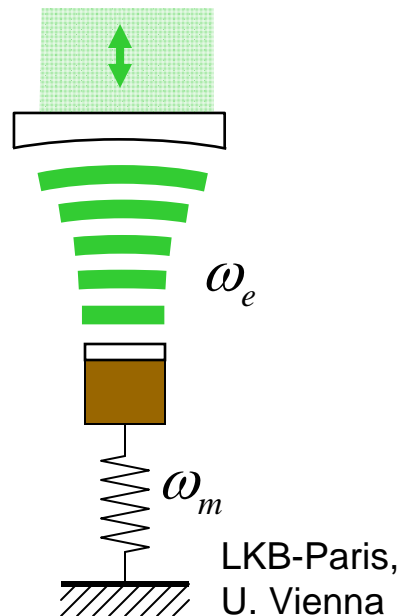
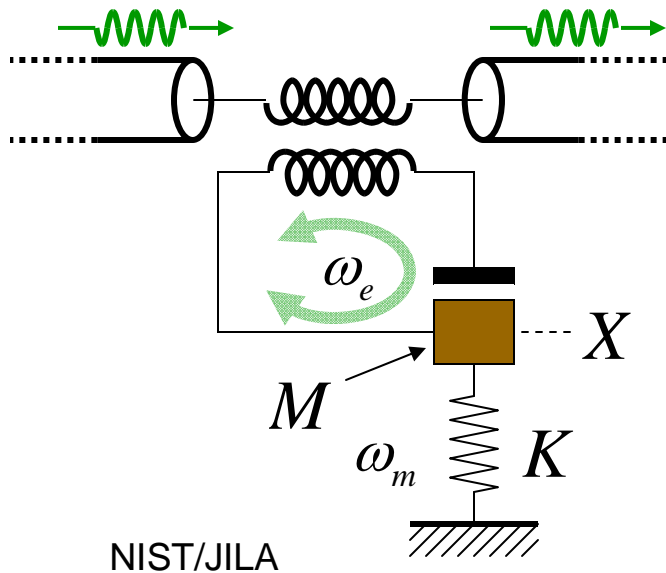


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Yale,  
EPFL  
Caltech

# QUANTUM ELECTRO/OPTO-MECHANICS HAMILTONIAN

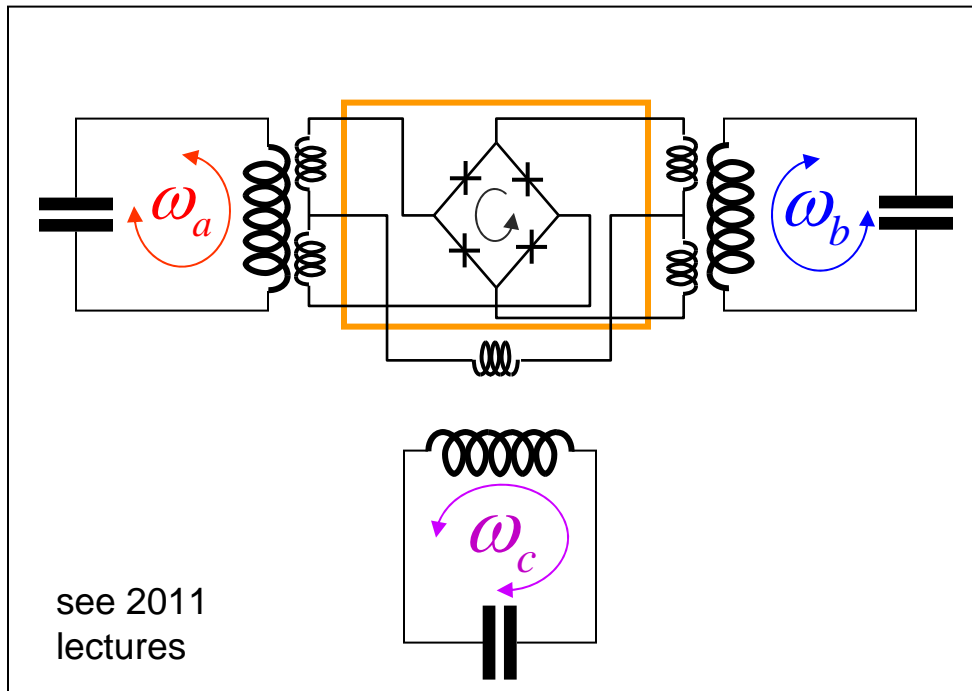
$$\frac{\hat{H}}{\hbar} = \left( \omega_e + \frac{i}{2} \kappa \right) \hat{a}^\dagger \hat{a} + \left( \omega_m + \frac{i}{2} \gamma \right) \hat{b}^\dagger \hat{b} + g_3 \left( \hat{b} + \hat{b}^\dagger \right) \hat{a}^\dagger \hat{a}$$

mostly external  $\nearrow$                       internal  $\nearrow$                        $g_3 = X_{ZPF} \frac{\partial \omega_e}{\partial X}$



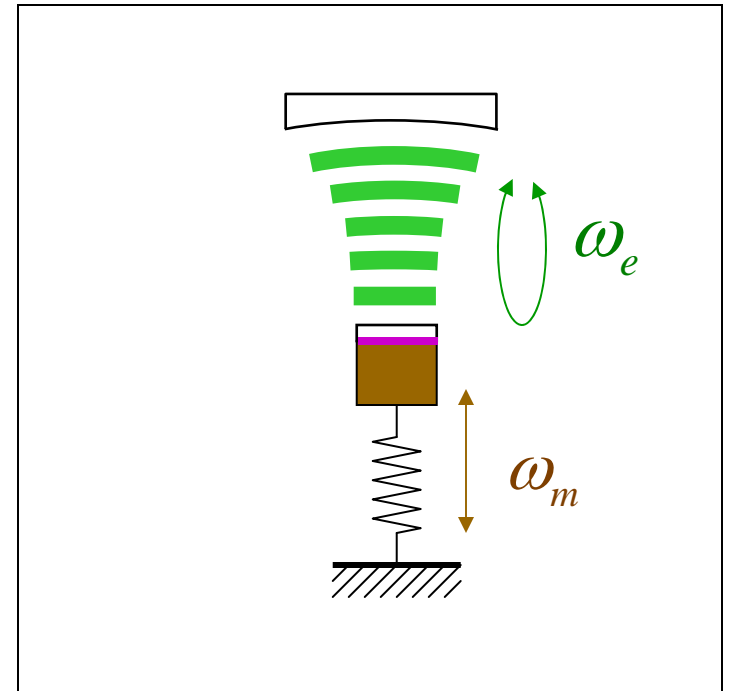
# THREE-WAVE COUPLING HAMILTONIAN

Josephson circuits: 3 non-linearly coupled oscillators



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

Optomechanics: 2 non-linearly coupled oscillators

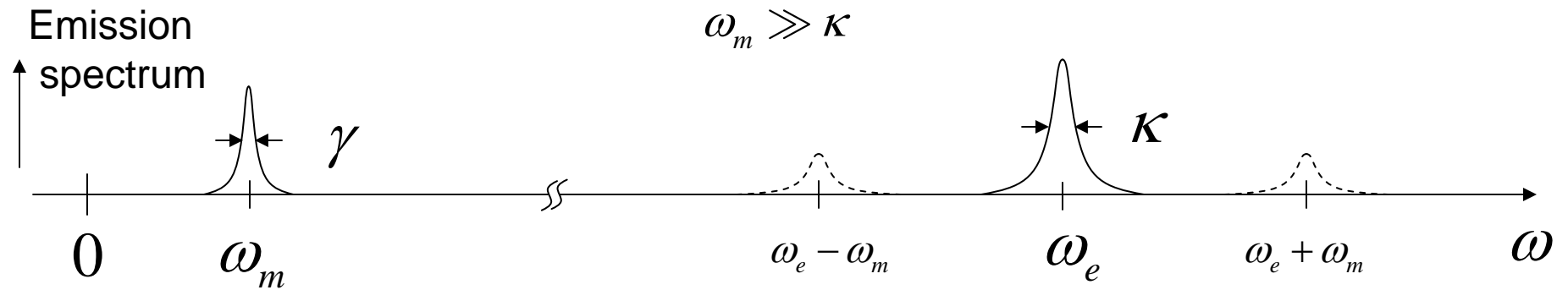


$$\frac{\hat{H}_{\text{sys}}}{\hbar} = \omega_e \hat{a}^\dagger \hat{a} + \omega_m \hat{b}^\dagger \hat{b} + g_3 \left( \hat{b} + \hat{b}^\dagger \right) \hat{a}^\dagger \hat{a}$$

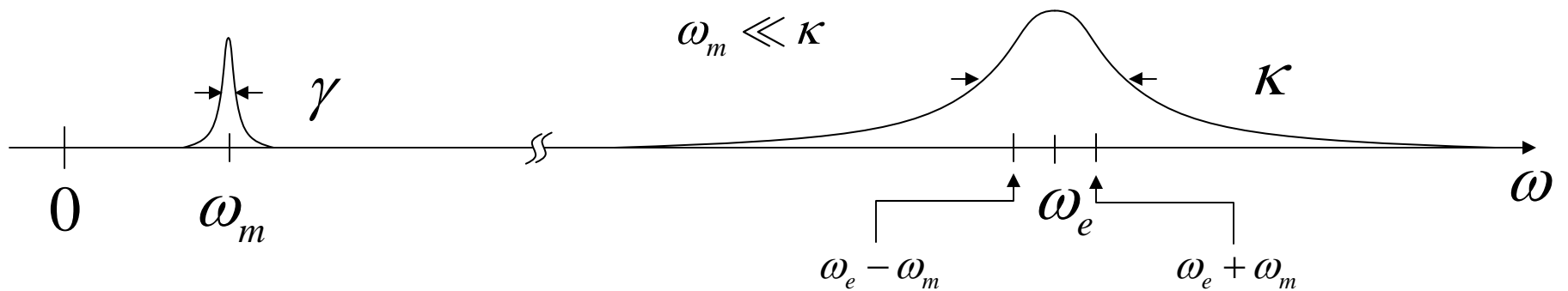


# FREQUENCY LANDSCAPE

Resolved sideband regime:



Un-resolved sideband regime:



# PHONON HEATING RATE

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

Heating rate of mechanical oscillator

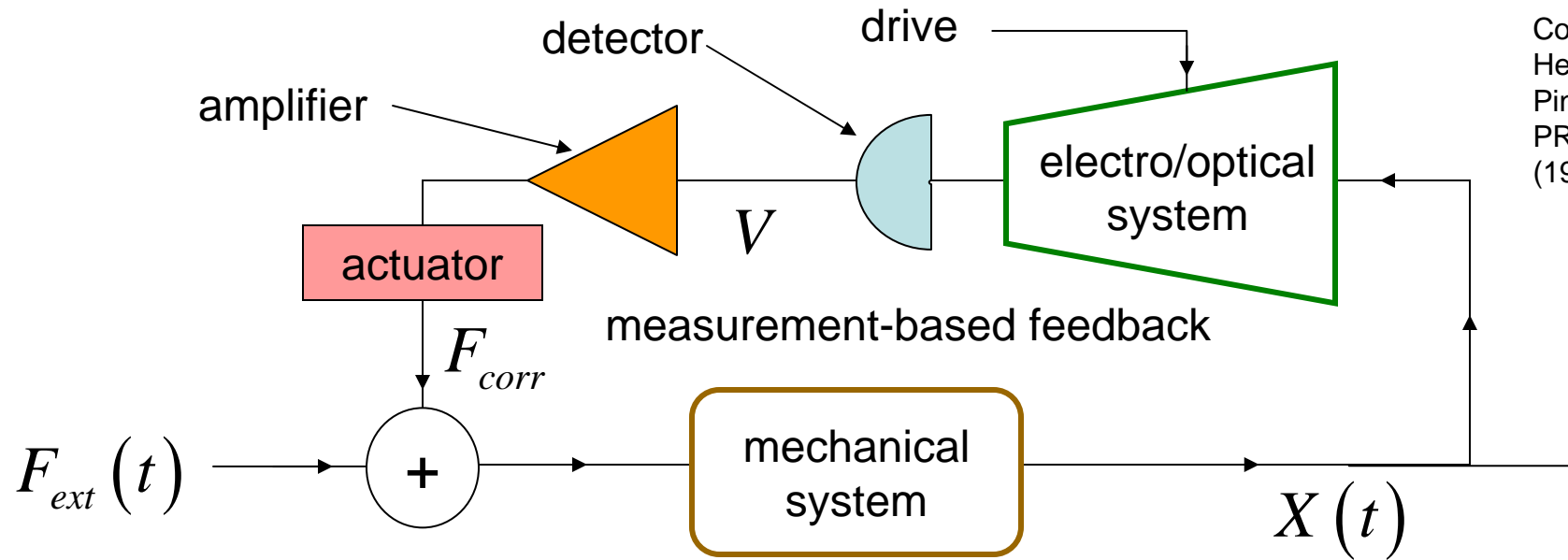
Phonon occupancy

Damping rate of mechanical oscillator

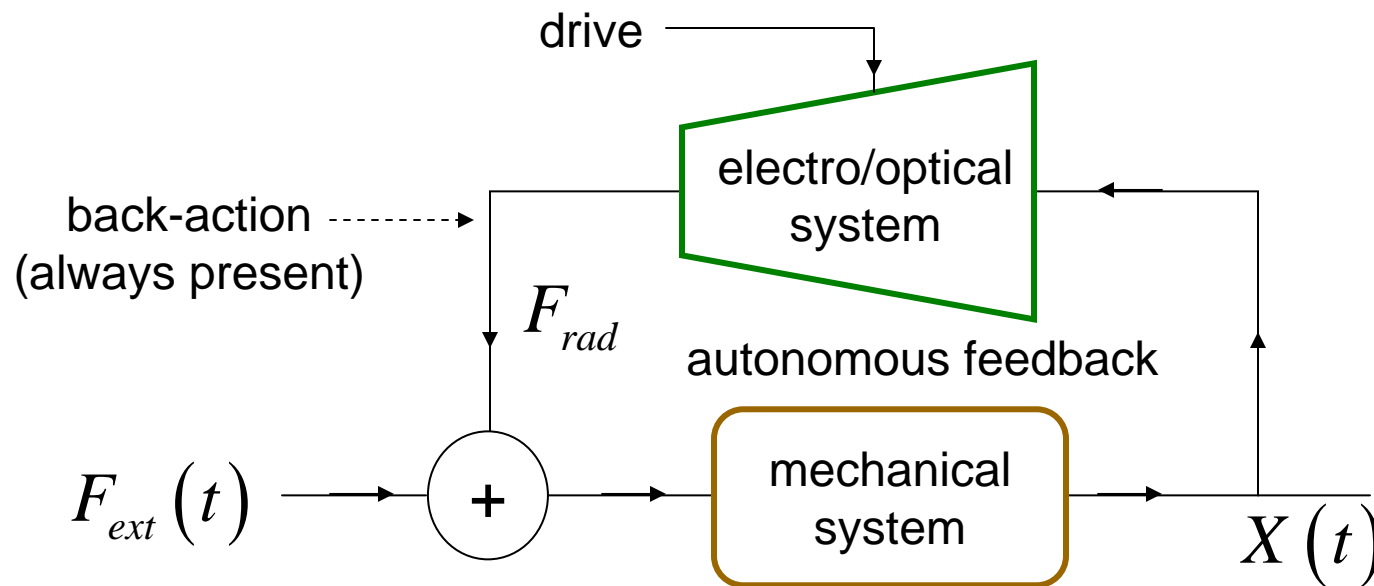
The diagram illustrates the equation  $\gamma_{eff} = n_{b,T} \gamma$ . Three arrows point from descriptive text to the terms in the equation: one from 'Heating rate of mechanical oscillator' to  $\gamma_{eff}$ , one from 'Phonon occupancy' to  $n_{b,T}$ , and one from 'Damping rate of mechanical oscillator' to  $\gamma$ .



# 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.

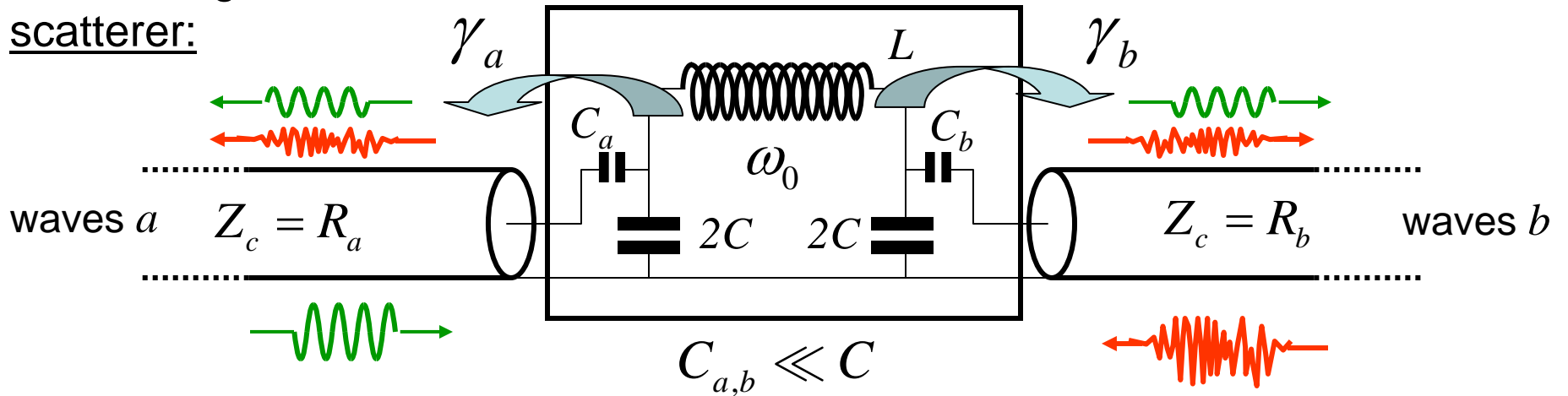
Measurement-based feedback will cool down to noise temperature of amplifier in feedback loop. Problem is that ground state is not an eigenstate of position  $X$  and amplifier usually adds noise.

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

$$S = \begin{bmatrix} \frac{\Gamma_a - \Gamma_b - i\Delta\omega}{\Gamma_a + \Gamma_b + i\Delta\omega} & -\frac{2\Gamma_a^{1/2}\Gamma_b^{1/2}}{\Gamma_a + \Gamma_b + i\Delta\omega} \\ -\frac{2\Gamma_a^{1/2}\Gamma_b^{1/2}}{\Gamma_a + \Gamma_b + i\Delta\omega} & \frac{\Gamma_b - \Gamma_a - i\Delta\omega}{\Gamma_a + \Gamma_b + i\Delta\omega} \end{bmatrix}$$

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

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

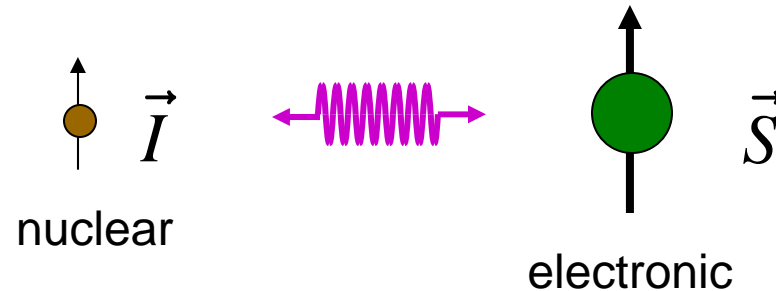
Interference: when  $\Delta\omega = 0$  &  $\gamma_a = \gamma_b$ , reflection vanishes!  
Waves are perfectly transmitted.

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:

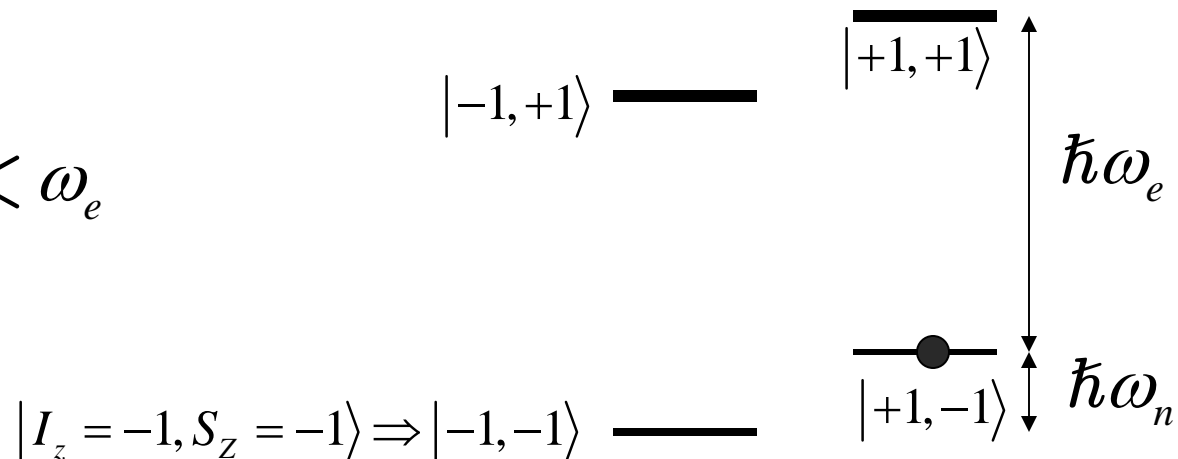


Hamiltonian contains  
electron-spin coupling:

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

Levels:

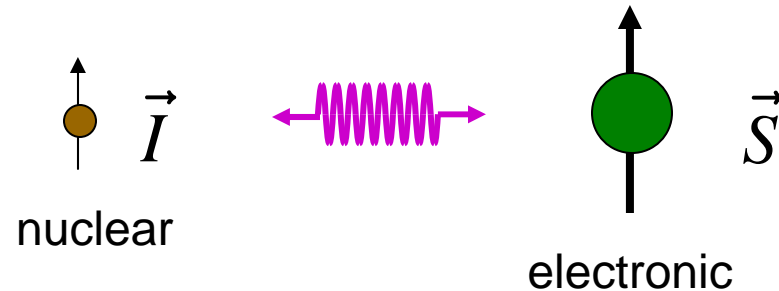
$$g \ll \omega_n \ll \omega_e$$



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

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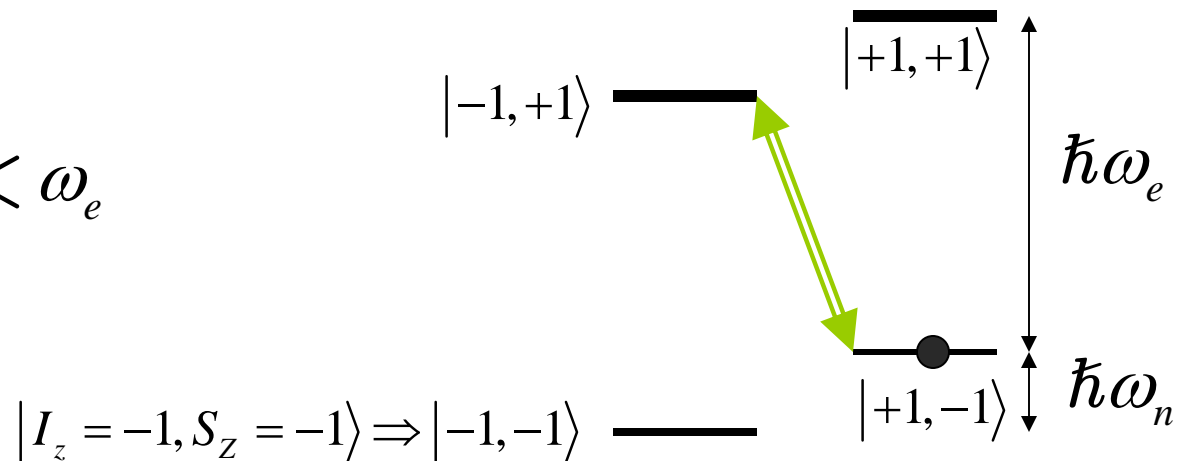


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Levels:

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

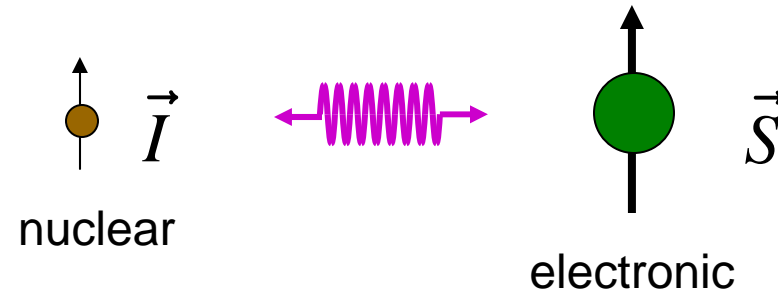


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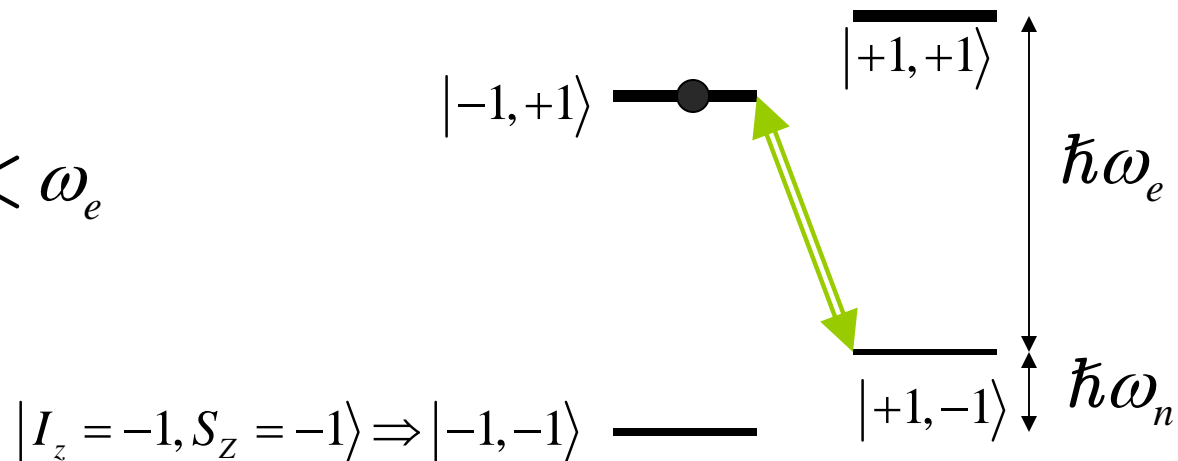


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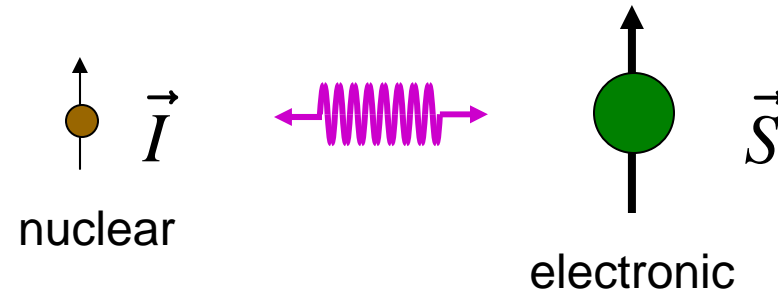
$$g \ll \omega_n \ll \omega_e$$



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

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

Two spins:

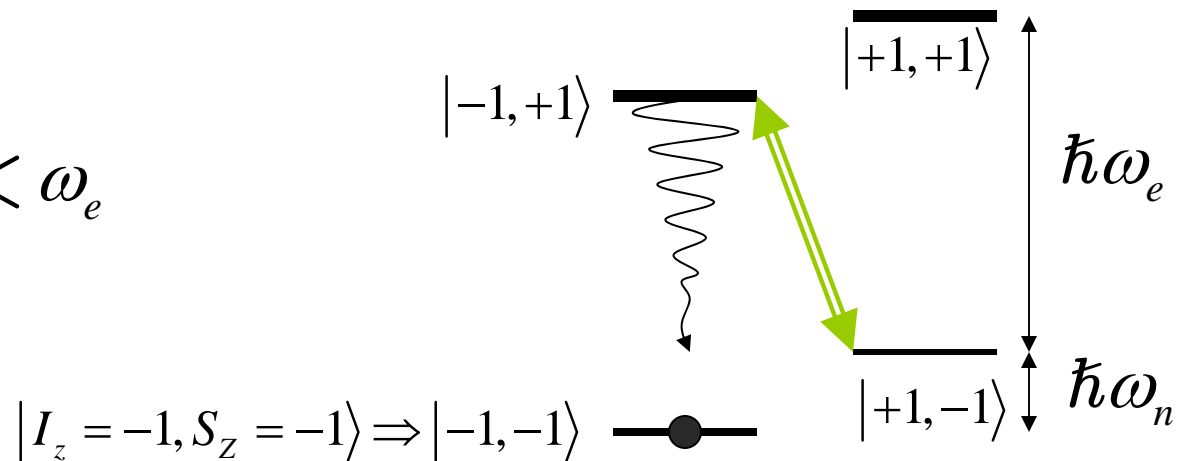


Hamiltonian contains  
electron-spin coupling:

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

Levels:

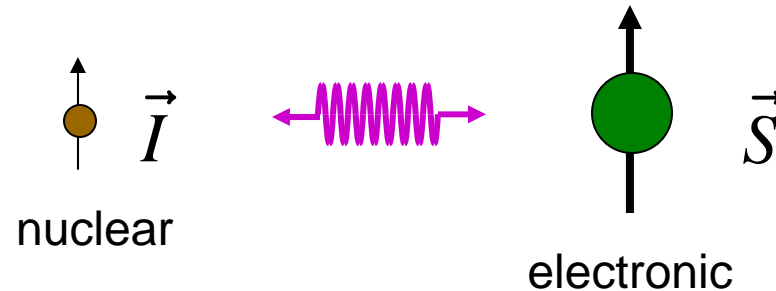
$$g \ll \omega_n \ll \omega_e$$



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

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

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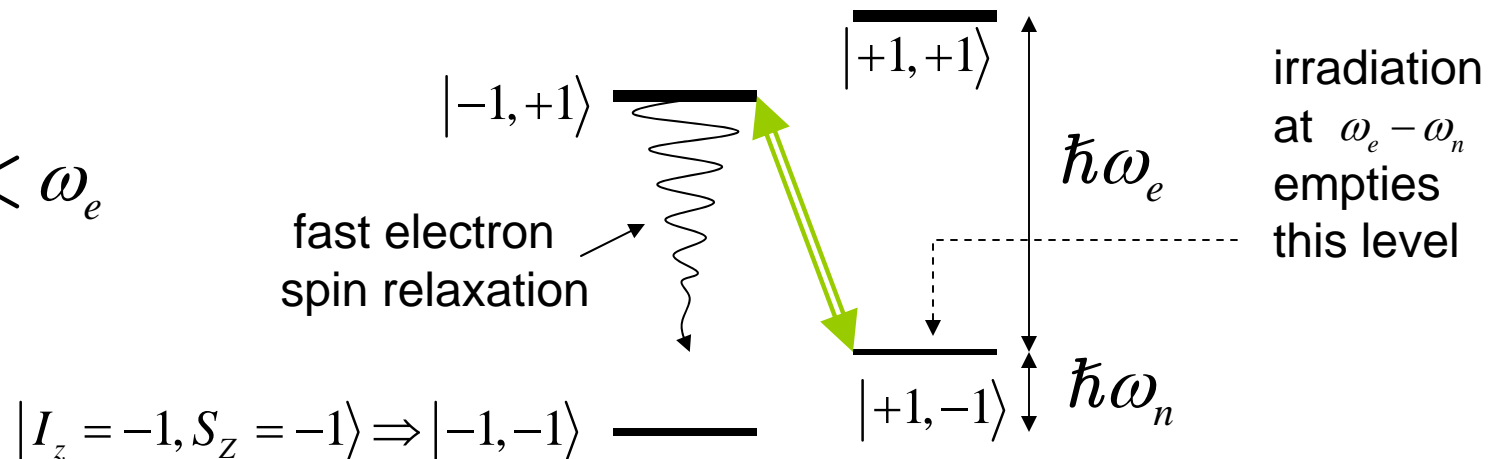


Hamiltonian contains  
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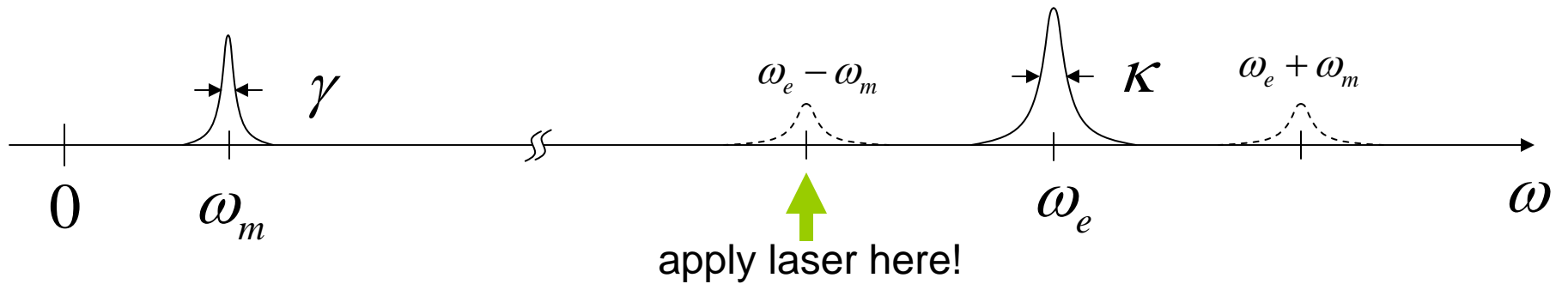
Levels:

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

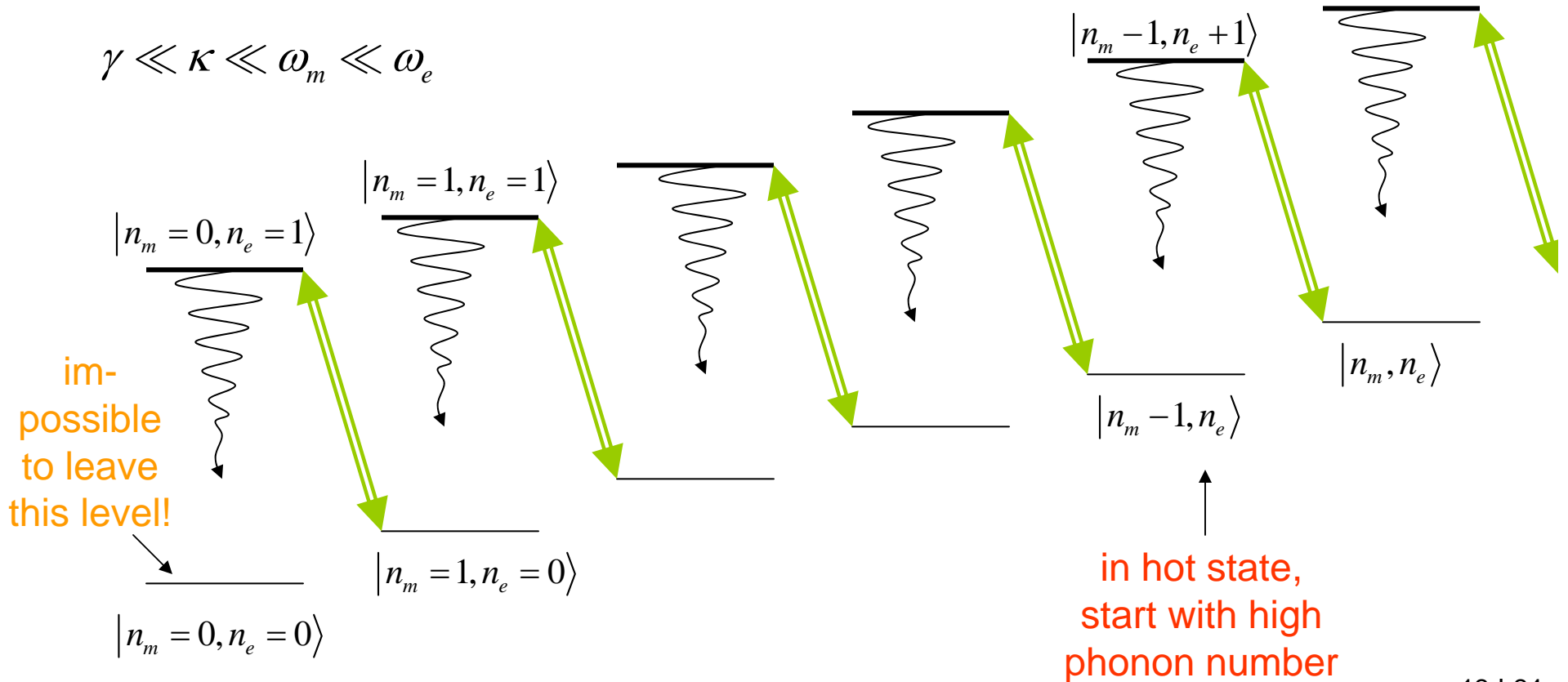


\* A. Abragam and M. Goldman, "Principles of dynamic nuclear polarisation", Rep. Prog. Phys., Vol 41, 1978

# DYNAMICAL COOLING OF OSCILLATOR MOTION IN THE RESOLVED SIDEBAND REGIME



$$\gamma \ll \kappa \ll \omega_m \ll \omega_e$$



# PROGRAM OF THIS YEAR'S LECTURES

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Lecture I: Introduction to nanomechanical systems

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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

- Braginsky, V. B., and F. Y. Khalili, "Quantum Measurements" (Cambridge University Press, Cambridge, 1992).
- Clarke, J. and Braginsky, A. I., eds., "The SQUID Handbook" (Wiley-VCH, Weinheim, Germany, 2006).
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- Cohen-Tannoudji, C., Dupont-Roc, J., Grynberg, G., "Photons and Atoms", (Wiley, New York, 1989)
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## Articles

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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

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**May 15: Rob Schoelkopf (Yale University, USA)**

*Quantum optics and quantum computation with superconducting circuits.*

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**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