RELATIONS de FLUCTUATION - THEORIE et EXPERIENCE

Objectif

Le but du cours est de familiariser les auditeurs avec les développements récents de la physique hors d'équilibre des systèmes mesoscopiques centrés autour des Relations de Fluctuation. Ces relations généralisent loin d'équilibre les lois classiques de la physique statistiques des processus irréversibles. Nous allons discuter aussi bien leurs aspects théoriques que leur vérification expérimentale.

Plan du cours

1. Rappel des notions de la mécanique statistique d'équilibre - liens avec la réponse linéaire
- états de Gibbs
- Théorème de Fluctuation-Dissipation, relations de Kramers-Kronig
- applications à la calibration de micro-systèmes (oscillateur harmonique, circuit électronique, pièges optiques, microscope a force atomique)

2. Modélisation de la dynamique hors d'équilibre
- systèmes déterministes : forces conservatives et non conservatives, systèmes thermostatés
- systèmes aléatoires : processus de Markov, dynamique de Langevin
- Thermodynamique stochastique

3. Relations de Fluctuation transitoires
- renversement temporaire
- égalités de Jarzynski et relations de Crooks
- lien avec la 2eme Loi de la Thermodynamique
- relations de Evans-Searles et de Hatano-Sasa
- application a l'oscillateur harmonique, mesure sur molécule unique et piège optique hors d'équilibre

4. Relations de Fluctuations stationnaires
- états stationnaires hors d'équilibres (NESS)
- grandes déviations
- Théorème de Gallavotti-Cohen
- relations stationnaires pour la dynamique de Langevin
- exemples d'applications expérimentales dans des systèmes linéaires et non linéaires
- utilisation des relations de uctuation pour mesurer la puissance d'un moteur moléculaire

5. La réponse linéaire hors d'équilibre - théorie et expérience
- généralisations autour des NESS
- le cas de la dynamique de relaxation

Measuring out of equilibrium fluctuations

Measuring out of equilibrium fluctuations

Out of equilibrium fluctuations :

1. Chaotic dynamics

2. Stochastic systems

Measuring out of equilibrium fluctuations

Out of equilibrium fluctuations :

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2. Stochastic systems

   a. System in contact with an out of equilibrium bath
   b. System in contact with several heat baths at different temperatures
   c. System driven by an external force

Measuring out of equilibrium fluctuations

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What can be measured in these systems?

- Fluctuation Dissipation Theorem
- Fluctuation Theorem for work, heat and entropy
- Jarzinsky equality
- Time reversal symmetry and entropy production

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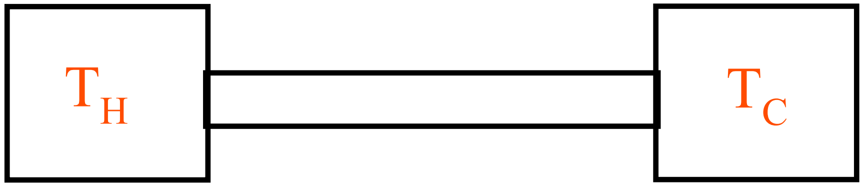
Fluctuations in out of equilibrium systems

Steady current through a system in contact between two reservoirs

Fluctuations in out of equilibrium systems

Steady current through a system in contact between two reservoirs

$T_H > T_C$



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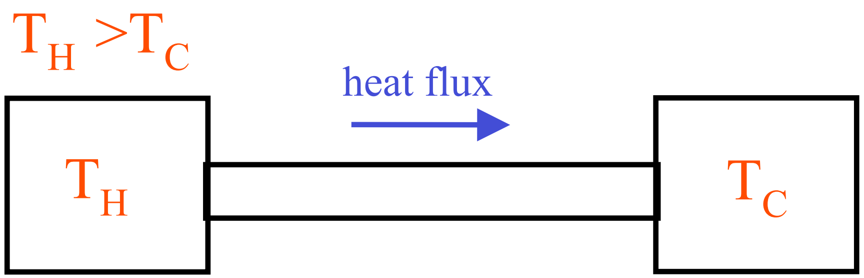

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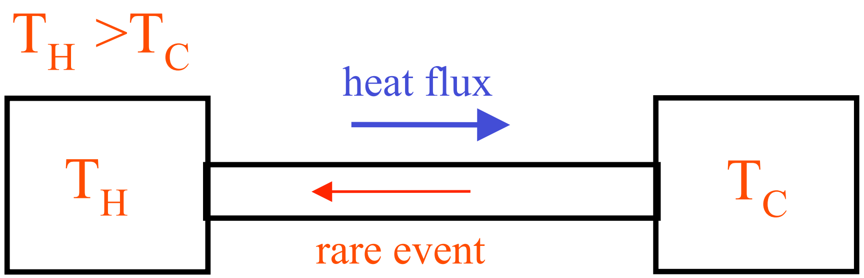

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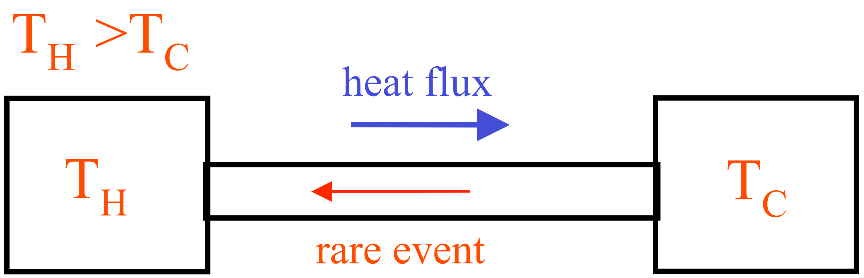

What is the probabilty that the heat flows from the cold to the hot reservoir ?

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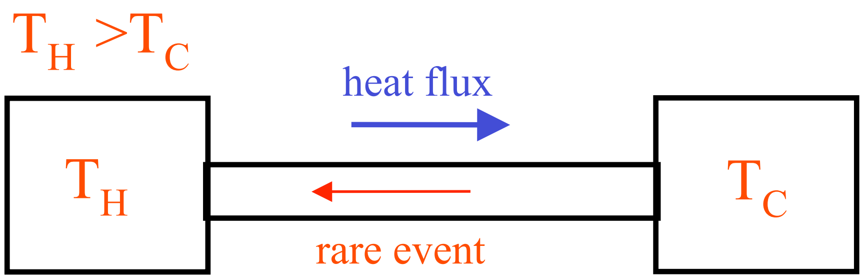

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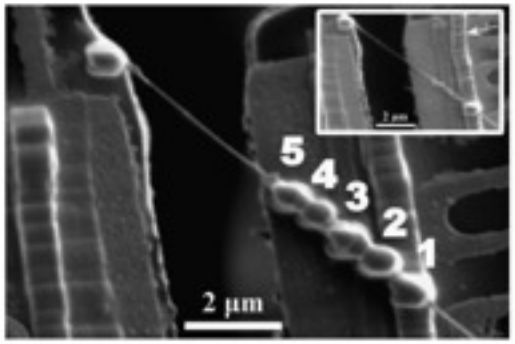
Thermal conductivity in nanotubes



C.W. Chang, et al.
PRL 101, 075903 (2008)

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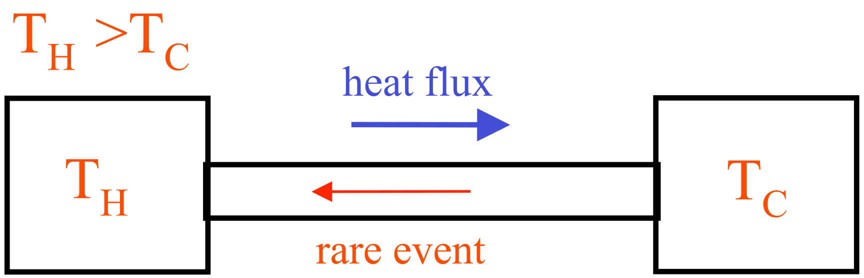

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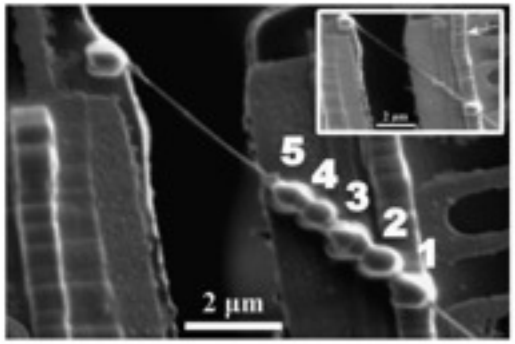

C.W. Chang, et al.
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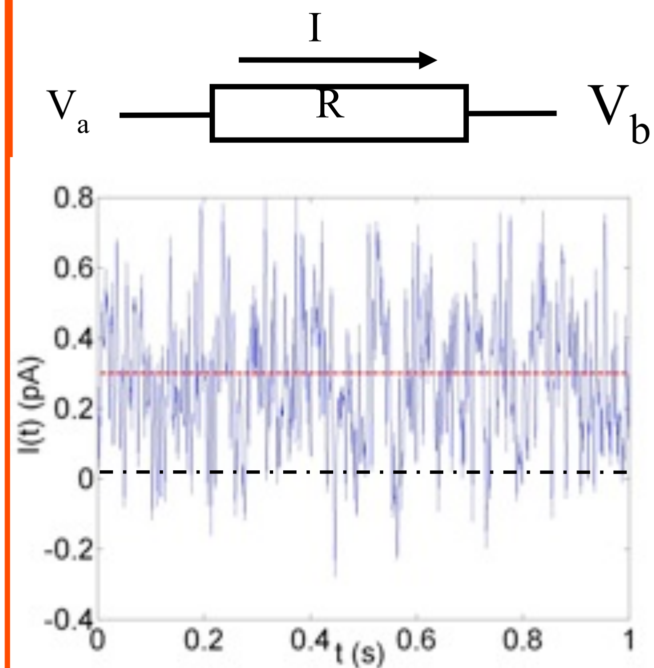
Electric current



R.Van Zon, et al
PRL 92, 130601 (2004).

N. Garnier, S. Ciliberto
PRE 71, 060101 (2005)

$$\bar{I} = \frac{(V_b - V_a)}{R}$$

Injected power

$$10^{-19} W$$

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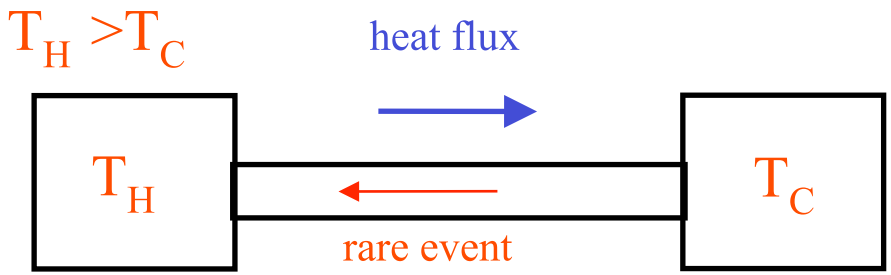

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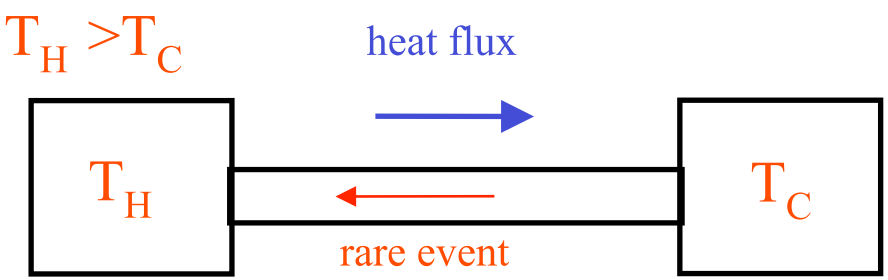

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Fluctuations in dynamical systems

Fluctuations in out of equilibrium systems

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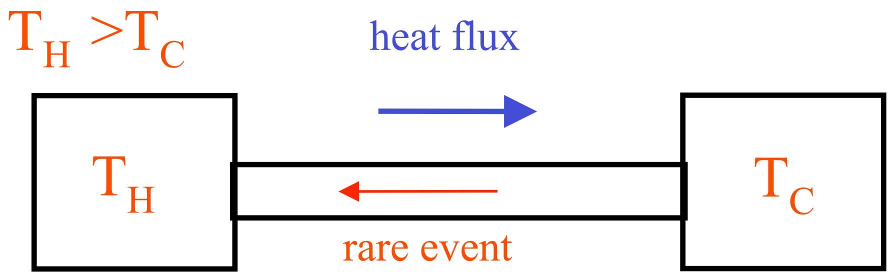

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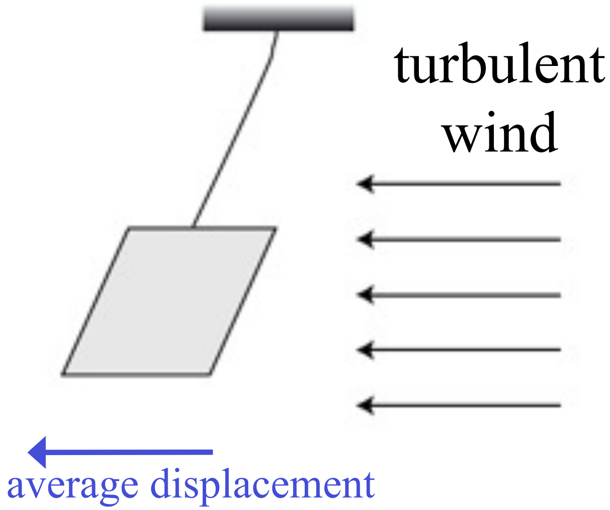

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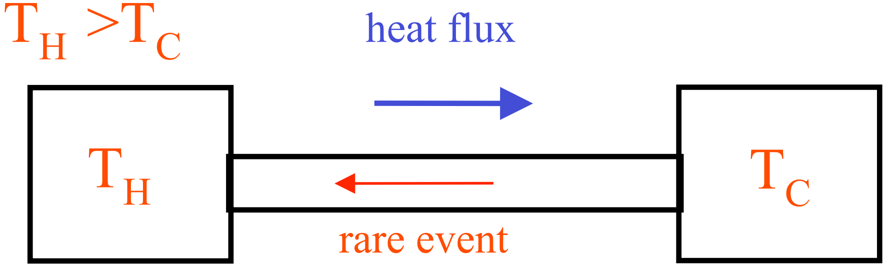

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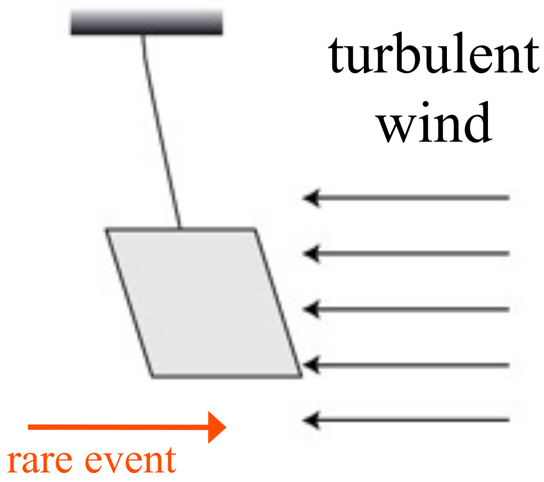

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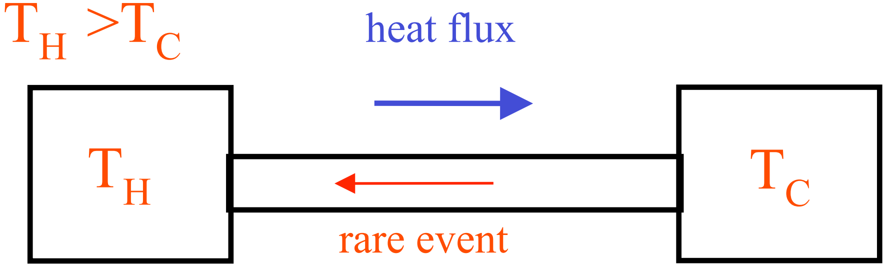

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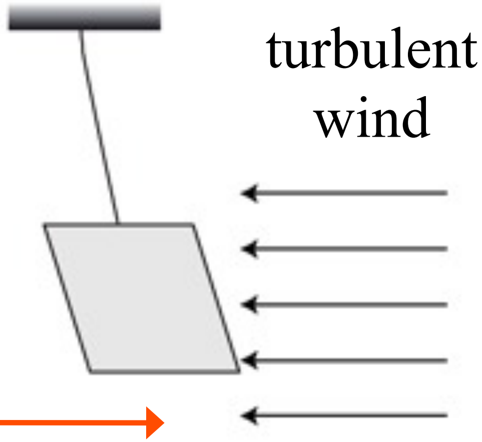

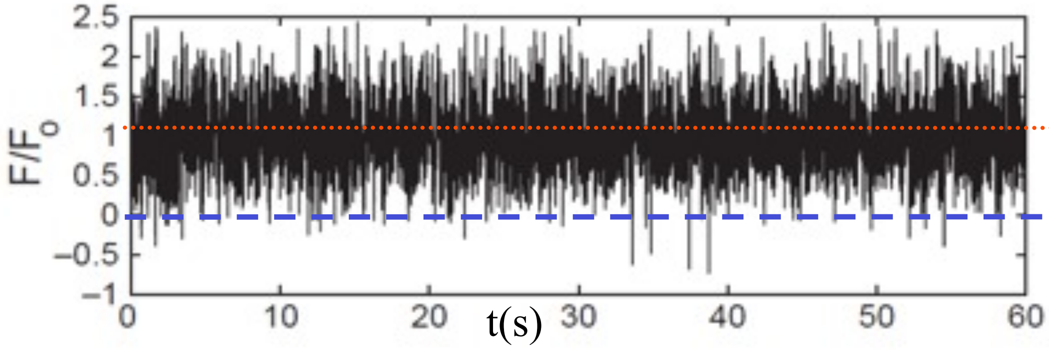

S. Ciliberto et al. / Physica A 340 (2004) 240 – 250

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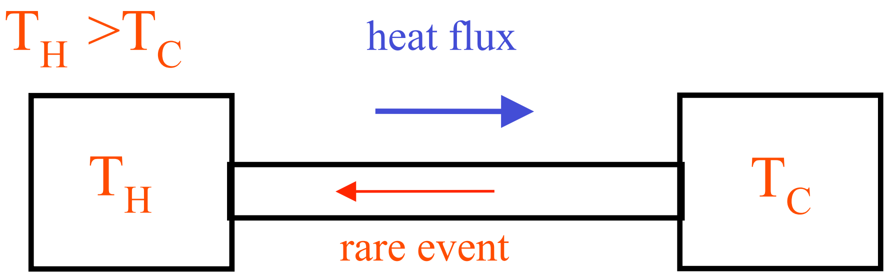

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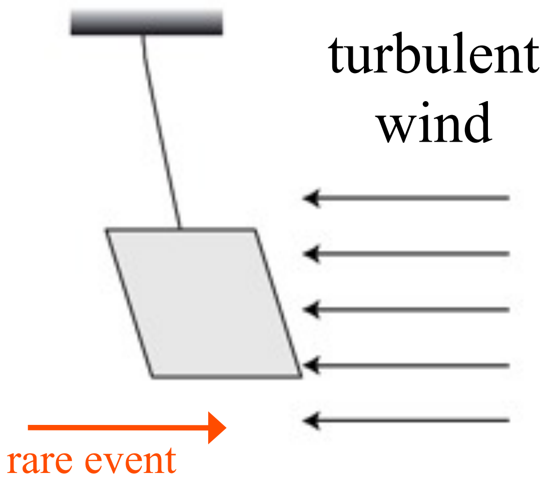

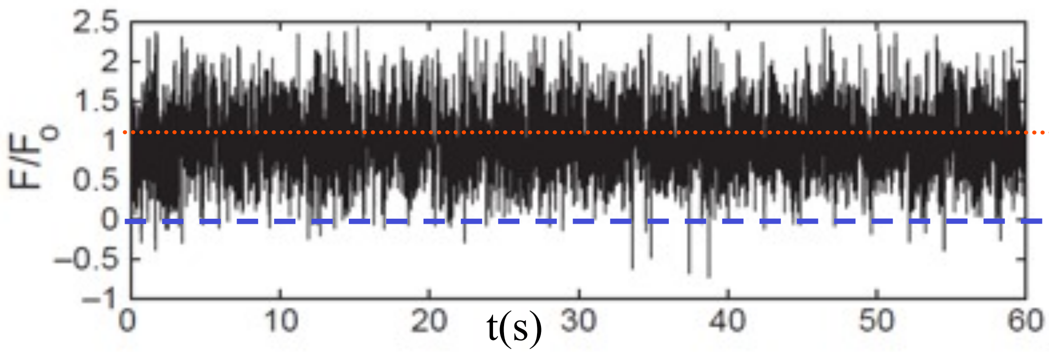

injected power $0.1 W$

S. Ciliberto et al. / Physica A 340 (2004) 240 – 250

Fluctuations in out of equilibrium systems

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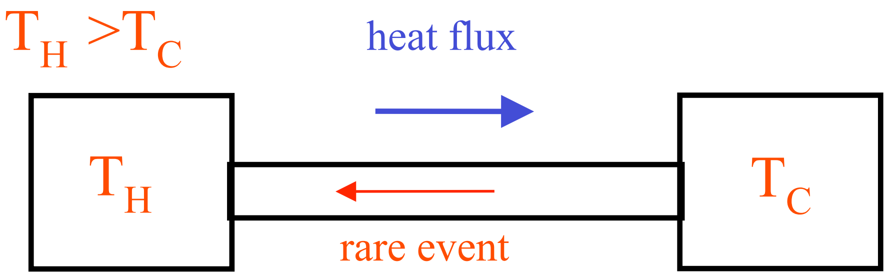
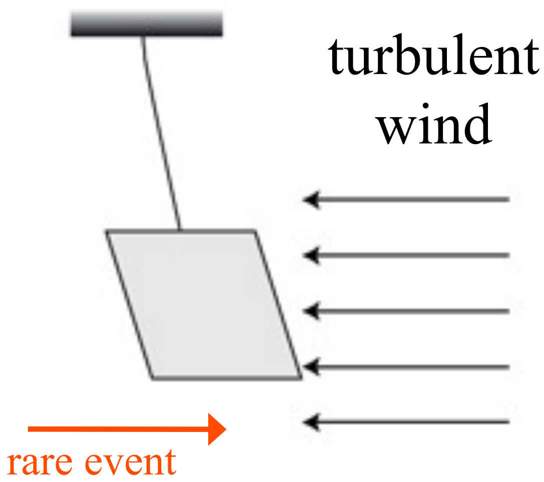


injected power $10^{-19} W$

Fluctuations in dynamical systems

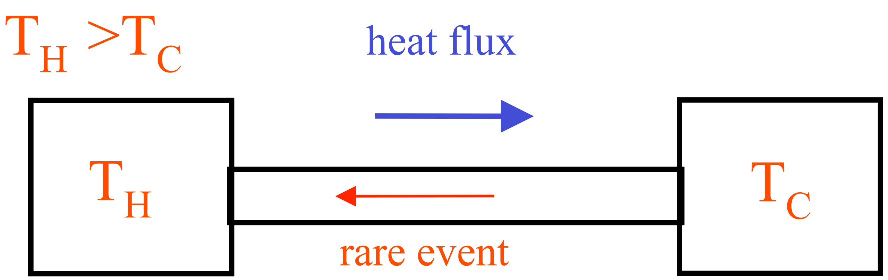


What is the probability that the object moves against the wind ?

injected power $0.1 W$

Fluctuations in out of equilibrium systems

Steady current through a system in contact between two reservoirs



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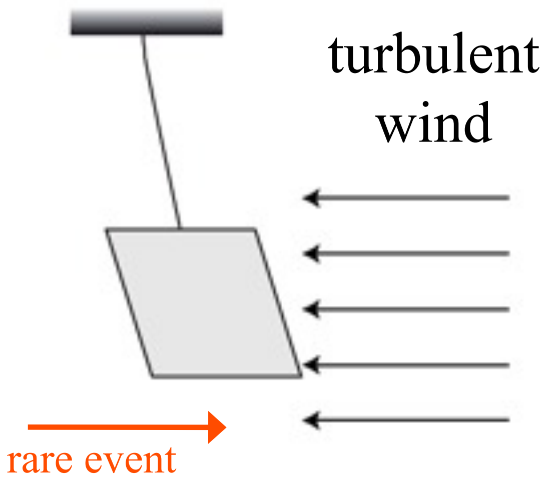
Fluctuation Theorem ?

Fluctuations in dynamical systems



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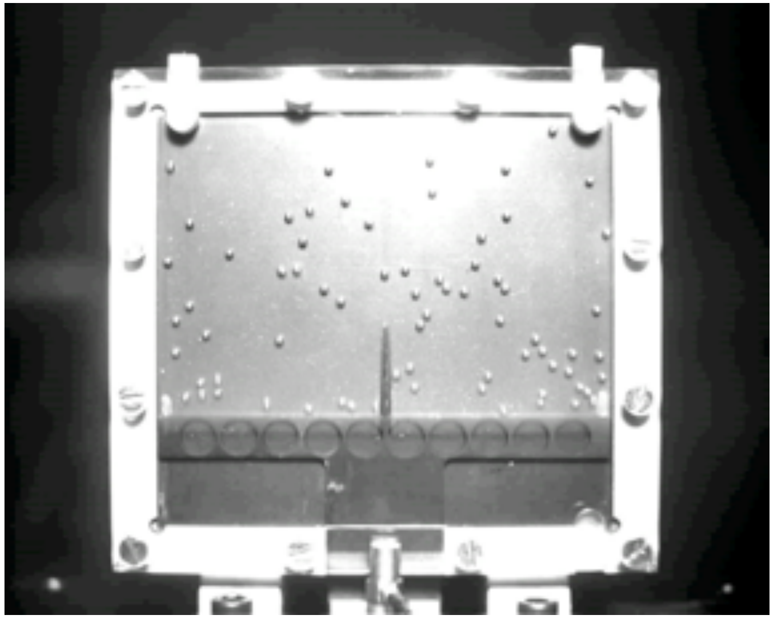
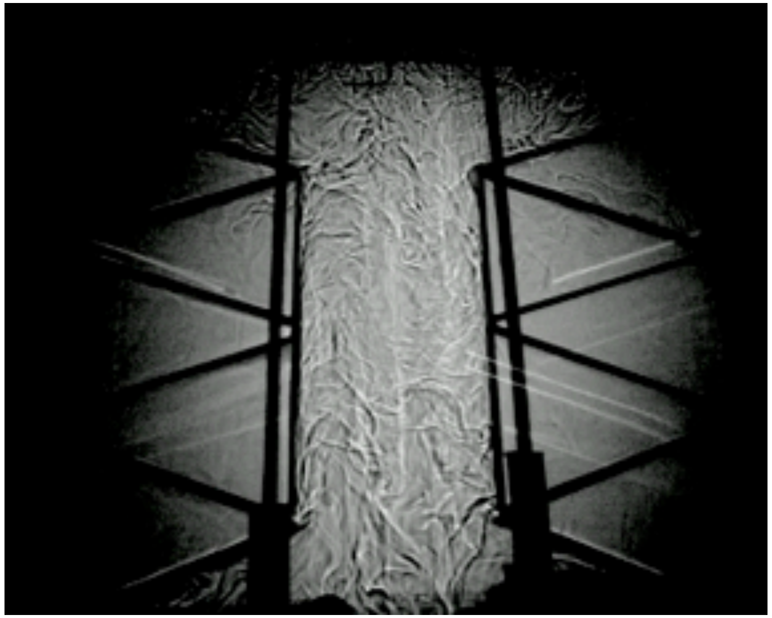
Examples of Dynamical Systems

Vibrated granular media



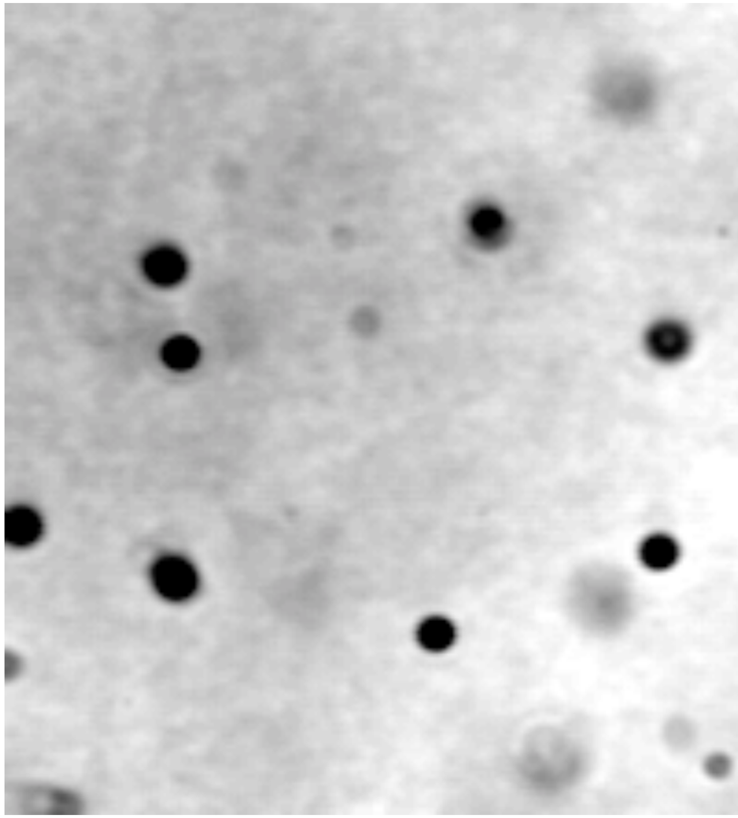
Thermal convetion in a fluid

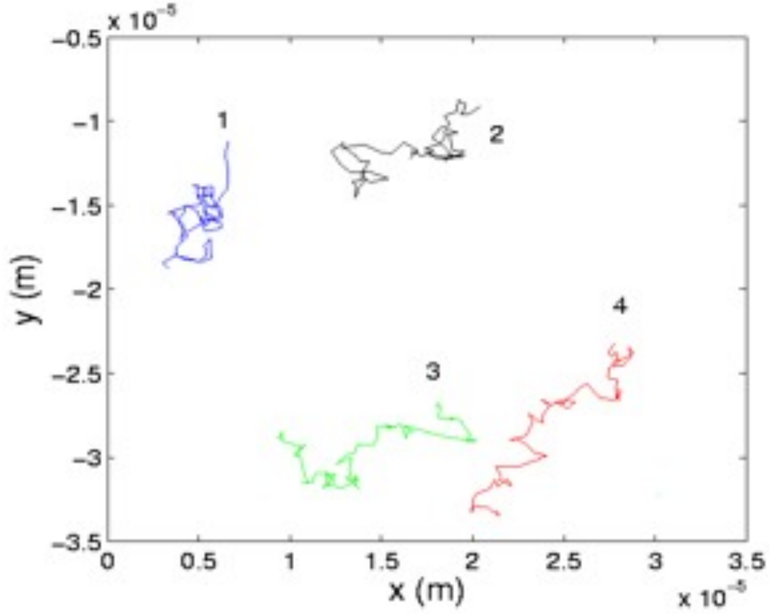
Cooled from above

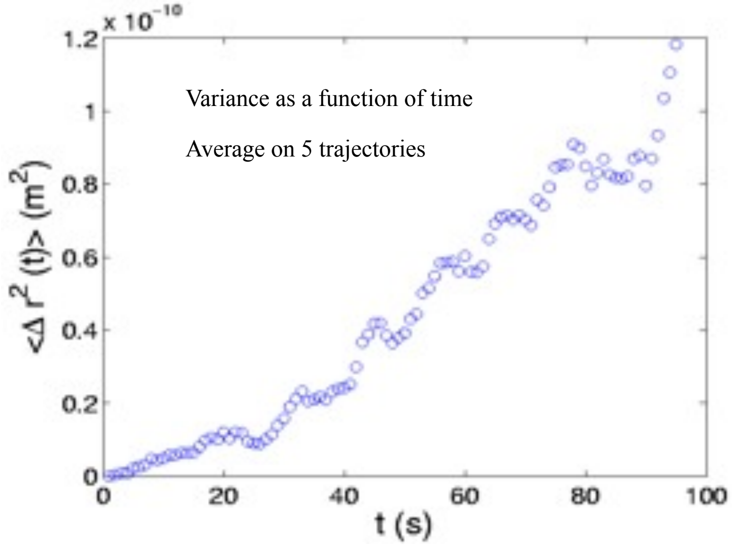


Heated from below

Brownian motion
EQUILIBRIUM

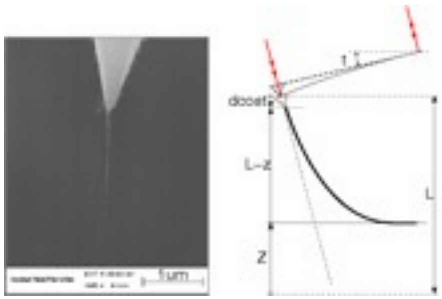




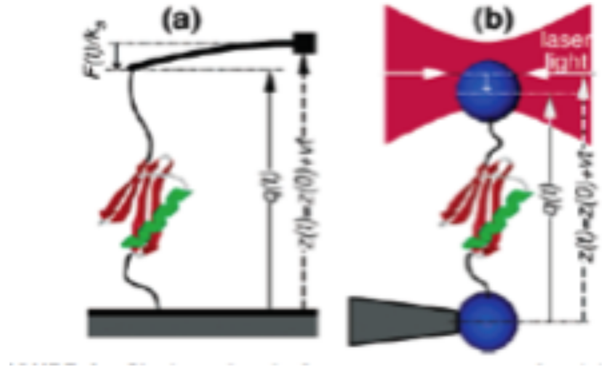


10 times faster than reality

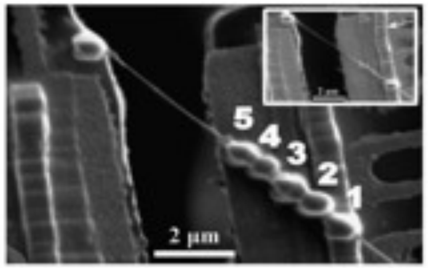
Examples of stochastic systems



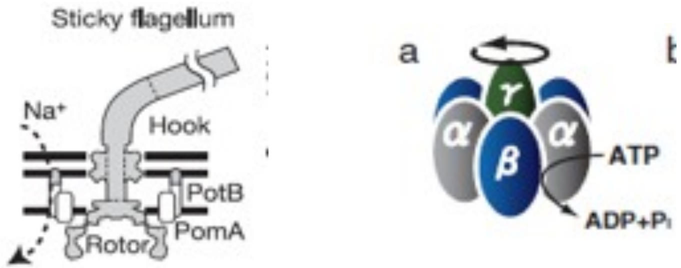
Mechanical properties of nanotubes



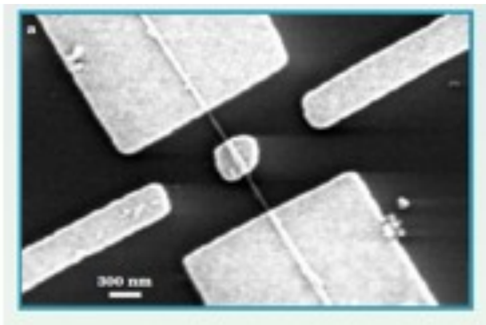
Stretched DNA Molecules



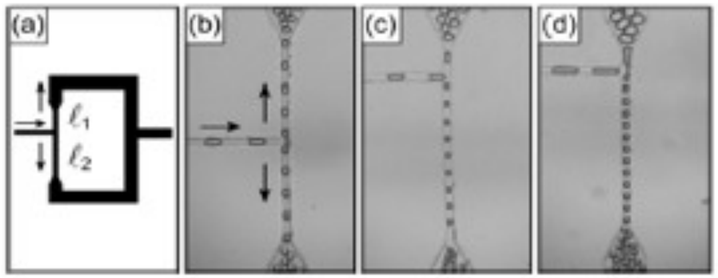
Thermal conduction in nanotubes



Molecular motors

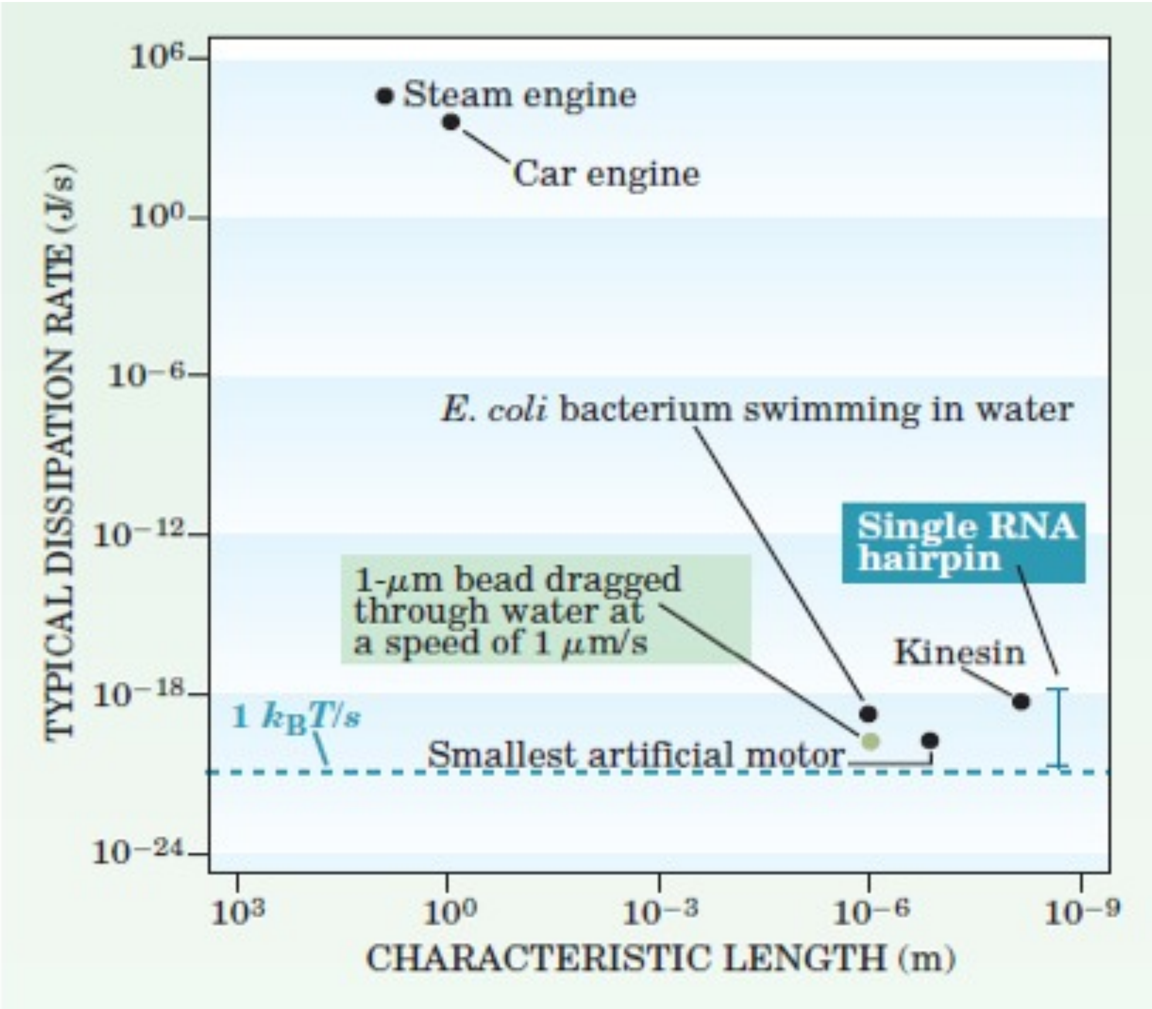


Micro Electro Mechanical Devices



Micro hydrodynamics

Dissipation



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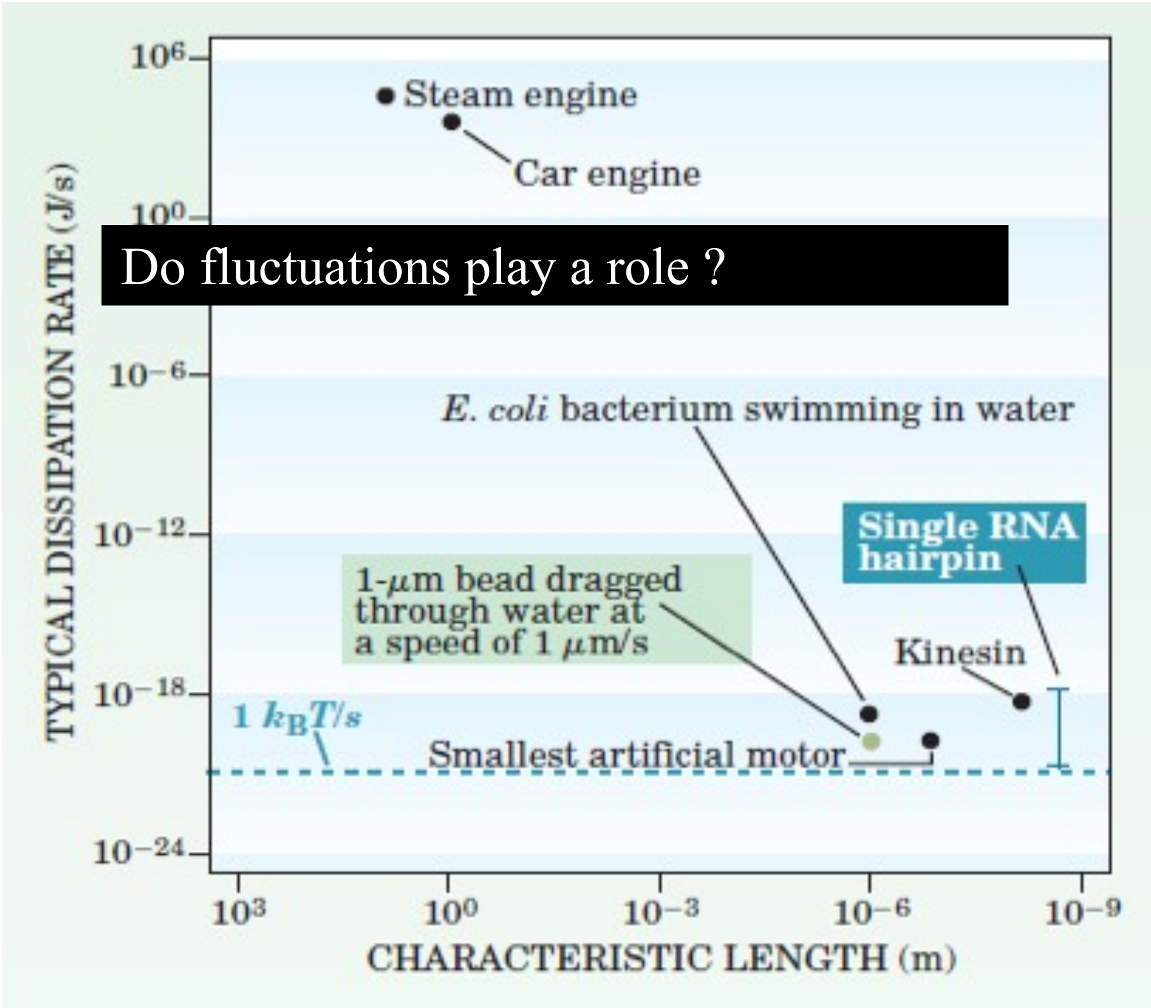
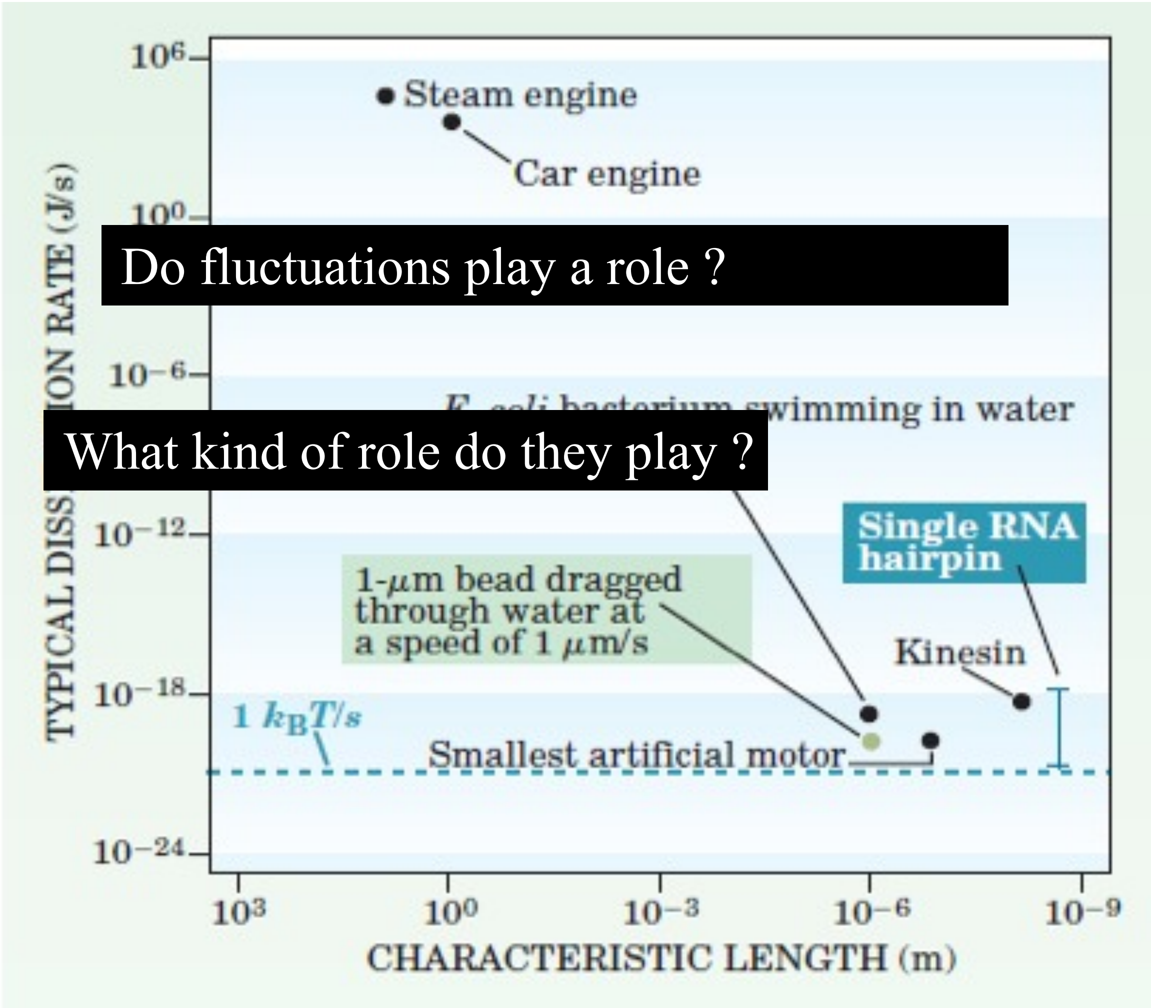
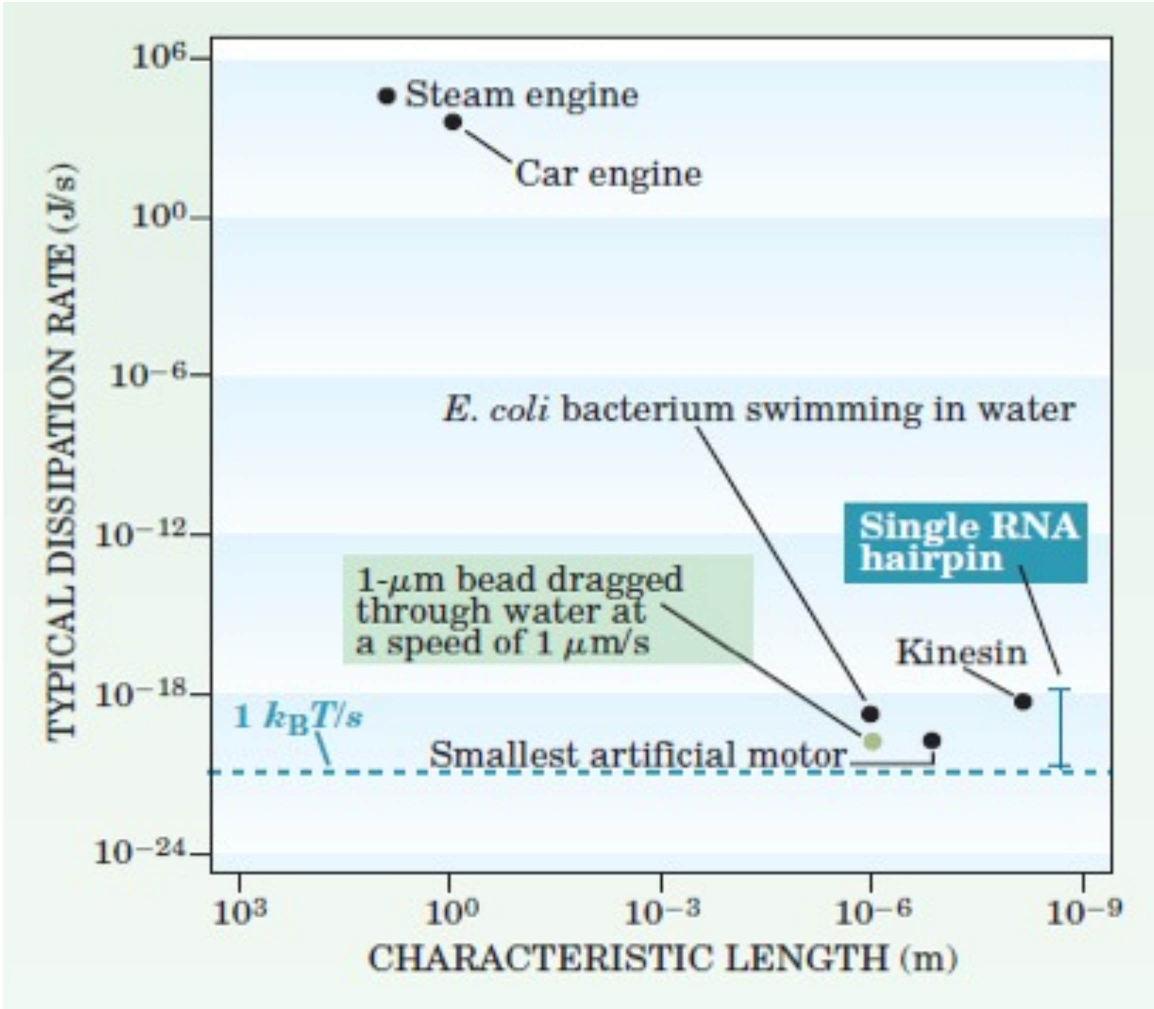


Do fluctuations play a role ?

Dissipation




Steam engine
Car engine
E. coli bacterium swimming in water
Single RNA hairpin
1-μm bead dragged through water at a speed of 1 μm/s
Kinesin
1 kBT/s
Smallest artificial motor
TYPICAL DISSIPATION RATE (J/s)
10^6
10^0
10^−6
10^−12
10^−18
10^−24
10^3
10^0
10^−3
10^−6
10^−9
CHARACTERISTIC LENGTH (m)

Outline

1) Work and heat fluctuations in out of equilibrium systems

1.1) Fluctuation Theorems

1.1a) Introduction and motivation

1.1.b) Stochastic systems

- Electric circuit
- Harmonic oscillator
- Optical traps

1.1.c) Dynamical Systems

- Power dissipation in a granular medium
- Turbulence (Rayleigh-Benard Convection
  Wind pressure)

1.2) Jarzinsky equality

- Harmonic oscillator
- Experiments in biophysics

2) Fluctuation DissipationTheorem out of equilibrium

2.1) Modified fluctuation Theorem out of equilibrium

2.2) Colloid during the sol gel transition

2.3) Liquid Crystal

3) Connection between thermodynamics and information

Motivation for experiments on fluctuations in dynamical and stochastic systems

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- Check the hypothesis done to prove FT

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- Check the hypothesis done to prove FT

- Test in experiments the analytical and numerical studies on FT

- What is the good variable to look at ?

Motivation for experiments on fluctuations in dynamical and stochastic systems

- Check the hypothesis done to prove FT

- Test in experiments the analytical and numerical studies on FT
- What is the good variable to look at ?

- Study of thermodynamics laws in out of equlibrium systems.
- Applications of fluctuation theorems to the measure of forces and heat exchanges

References

Book :

Nonequilibrium Statistical Physics of Small Systems: Fluctuation Relations and Beyond

Rainer Klages (Editor), Wolfram Just (Editor), Christopher Jarzynski (Editor), Heinz Georg Schuster (Series Editor)

Review Articles :

Fluctuations in out-of-equilibrium systems: from theory to experiment

S.Ciliberto, S. Joubaud, A. Petrosyan, Texte JSTAT (2010) P1200
arXiv:1009.3362

Fluctuations, Linear Response, and Currents in Out-of-Equilibrium Systems

S. Ciliberto, R. Gomez-Solano, and A. Petrosyan
Annu. Rev. Condens.Matter Phys. 2013. 4:235–61

Stochastic thermodynamics, fluctuation theorems and molecular machines

Seifert U., Rep. Prog. Phys., 75 (2012) 126001.

http://perso.ens-lyon.fr/sergio.ciliberto/Teaching/Cours_Phys_Stat/

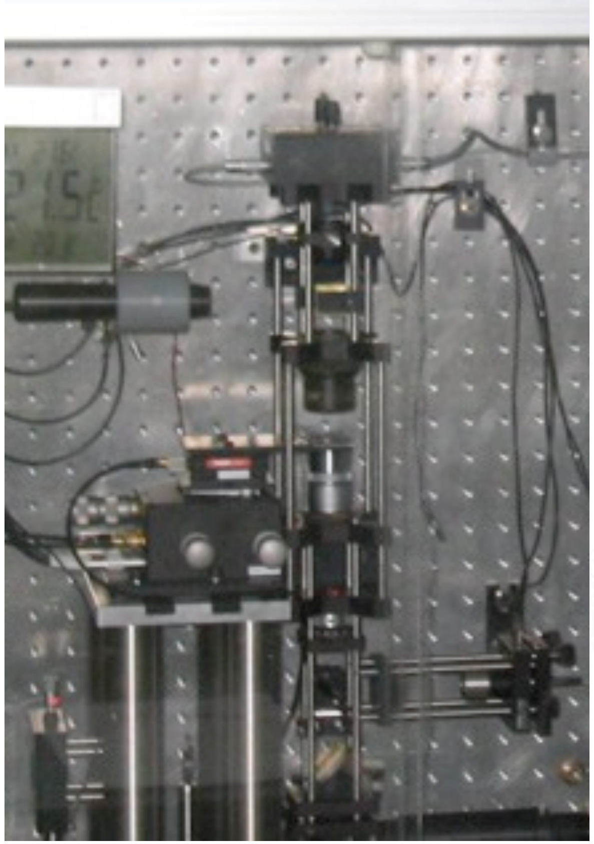
A few important notions on equilibrium

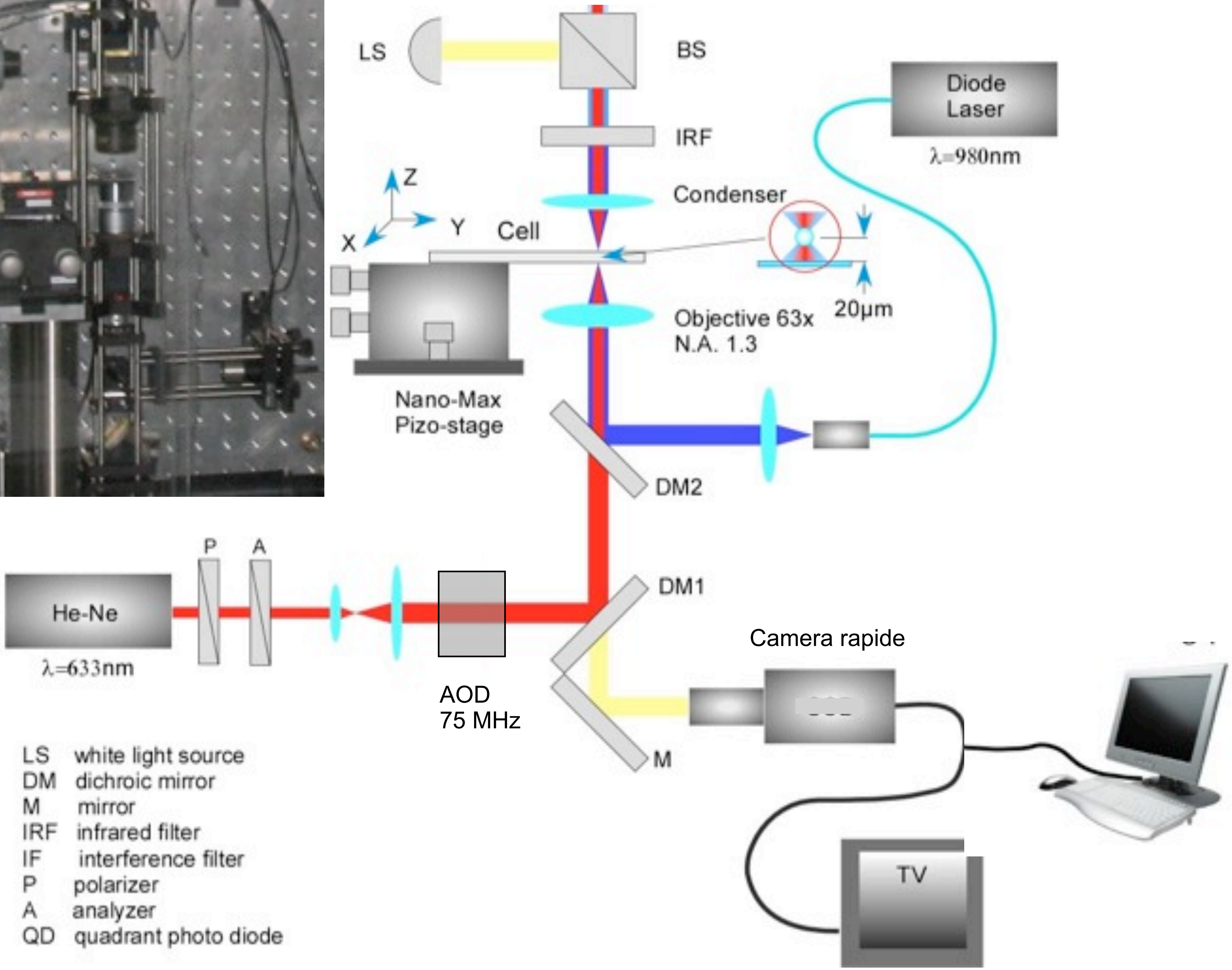
- Gibbs Statistics
- Detailed Balance
- Equipartition
- Fluctuation Dissipation Theorem (FDT)

We recall these concepts starting from experiments and showing that are actually useful for the calibration of the instruments.

- The optical trap
- An electric circuit.

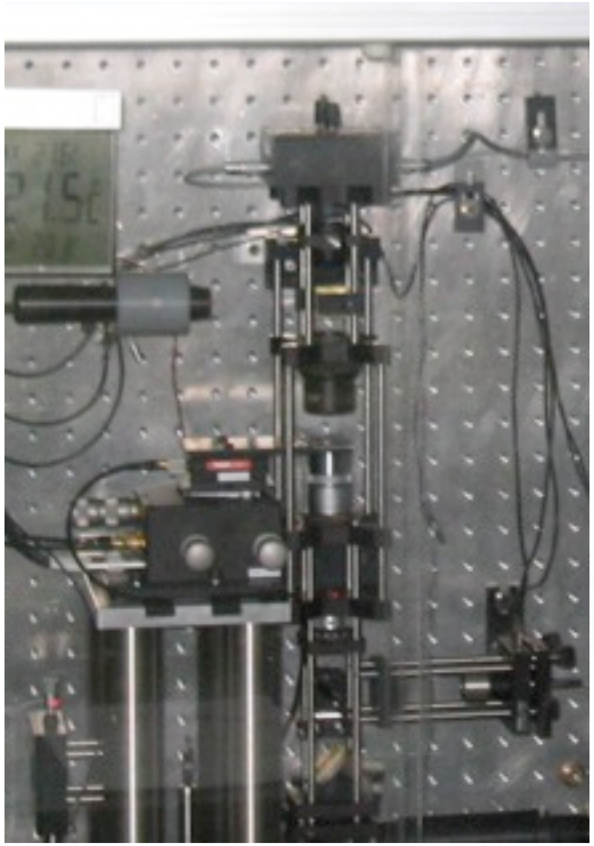
Optical traps

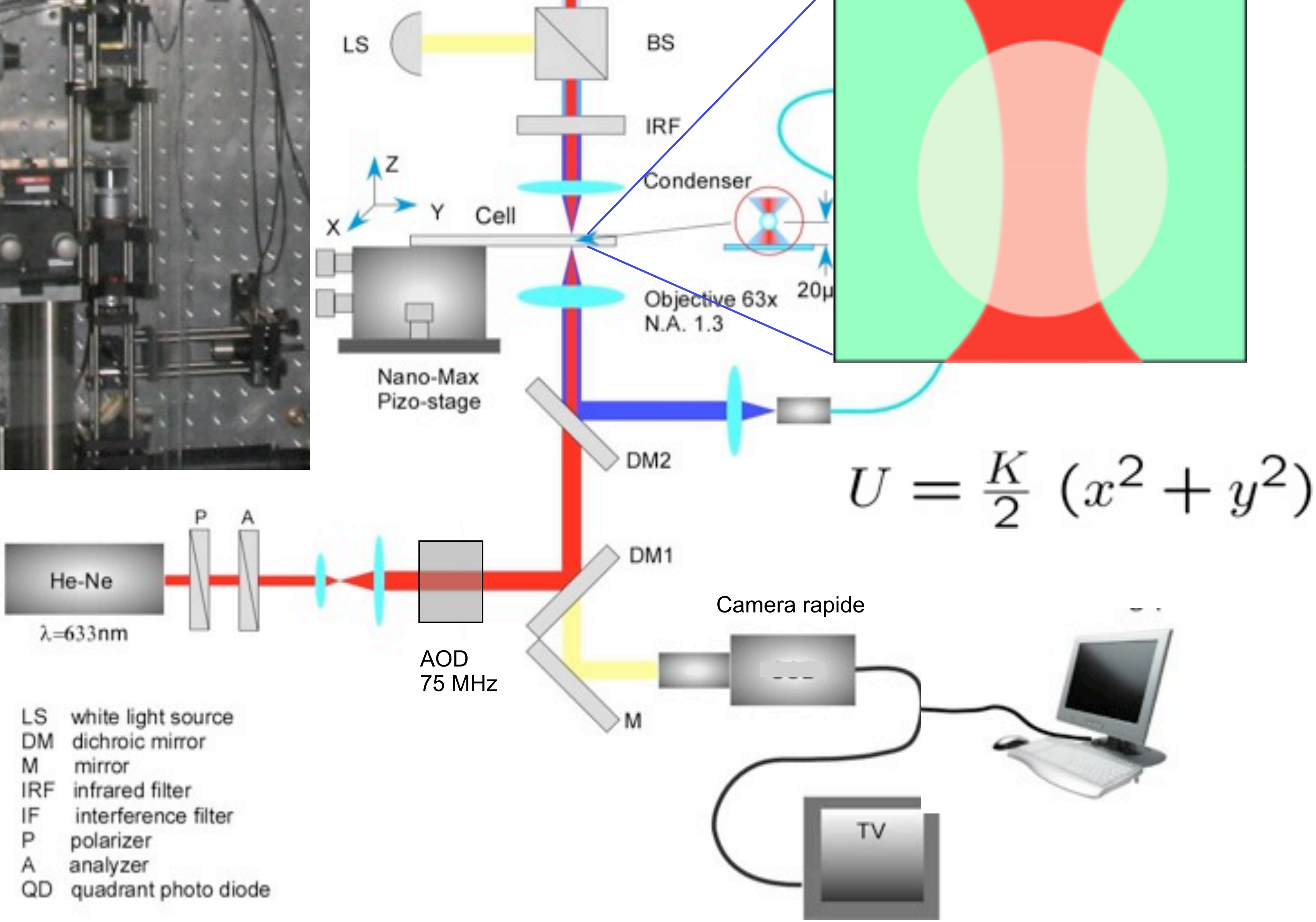




LS white light source
DM dichroic mirror
M mirror
IRF infrared filter
IF interference filter
P polarizer
A analyzer
QD quadrant photo diode

Optical traps





$$U = \frac{K}{2}\,(x^2 + y^2)$$

LS white light source
DM dichroic mirror
M mirror
IRF infrared filter
IF interference filter
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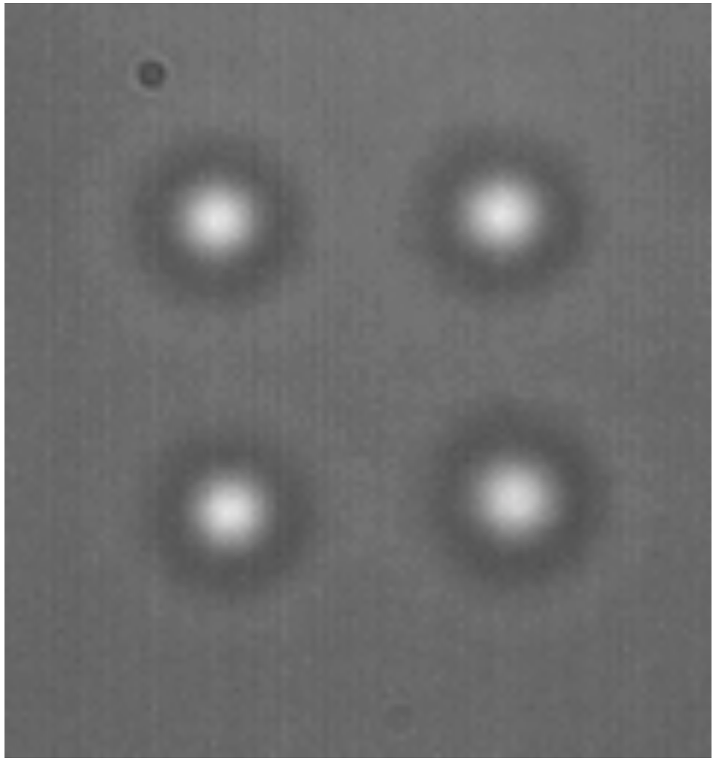
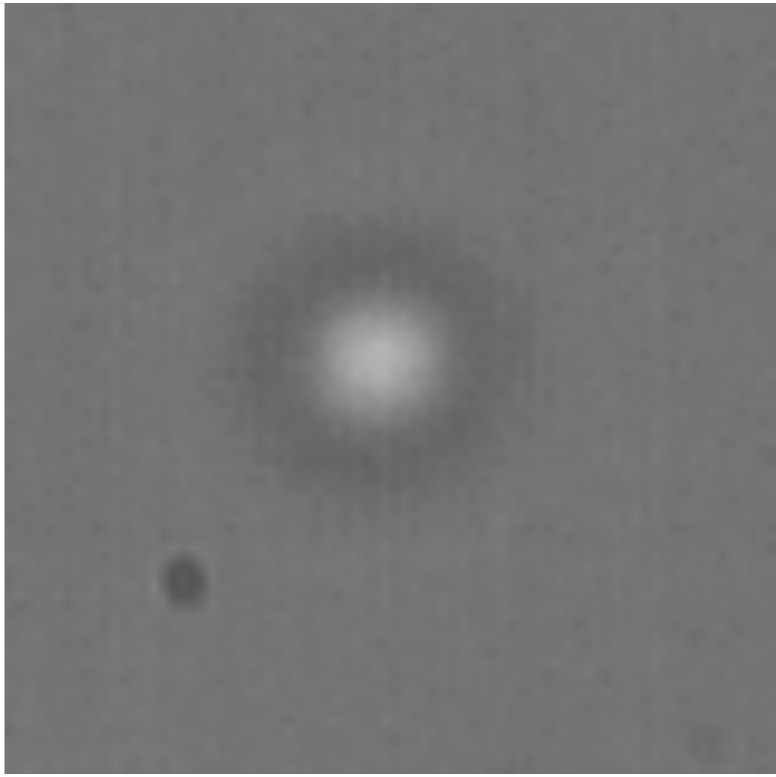
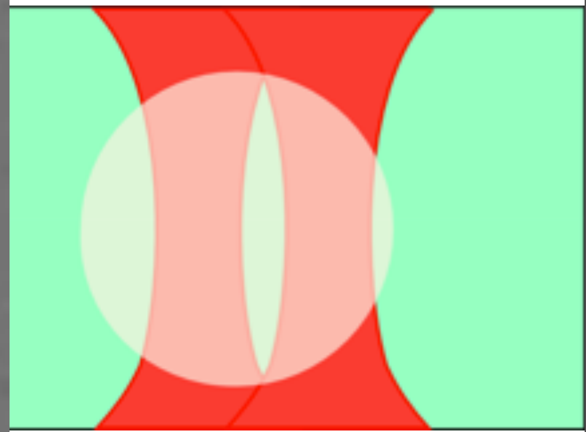
QD quadrant photo diode

Examples of traps







The Optical Tweezers principle

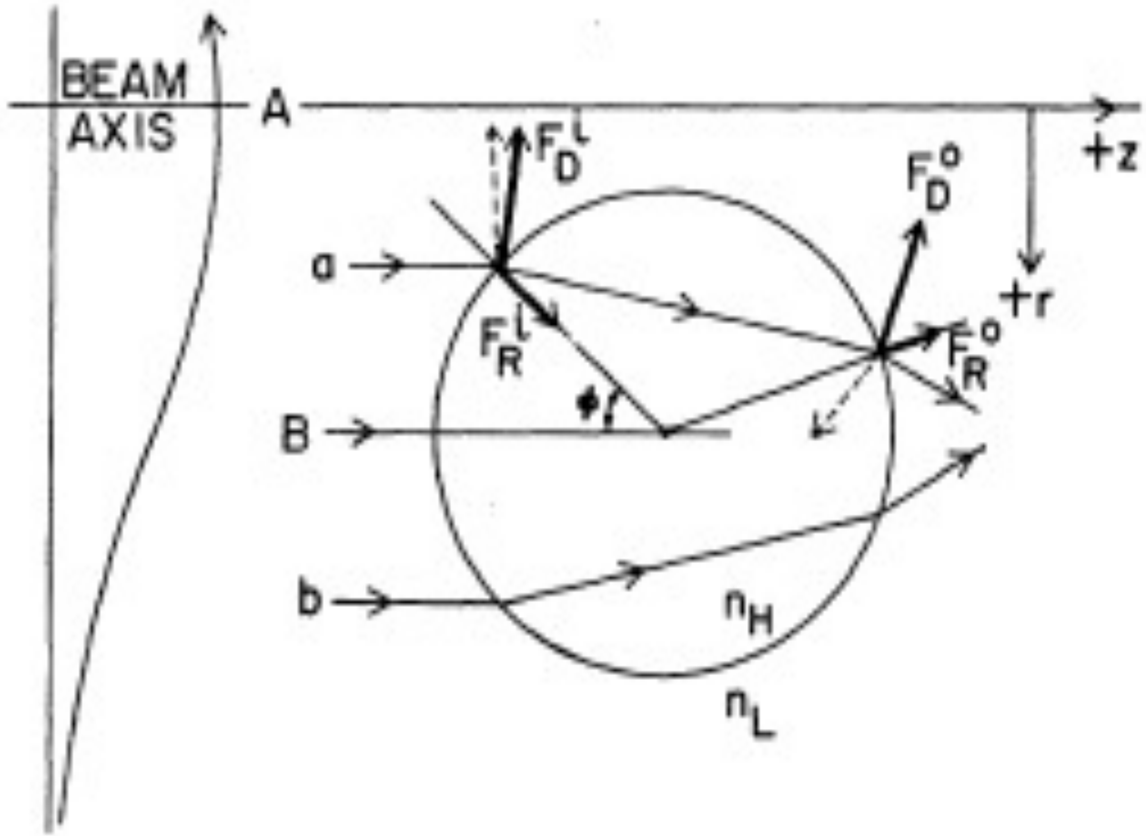


FIG. 2. A dielectric sphere situated off the axis A of a TEM_{00}-mode beam and a pair of symmetric rays a and b. The forces due to a are shown for $n_H > n_L$. The sphere moves toward $+z$ and $-r$.

The Optical Tweezers

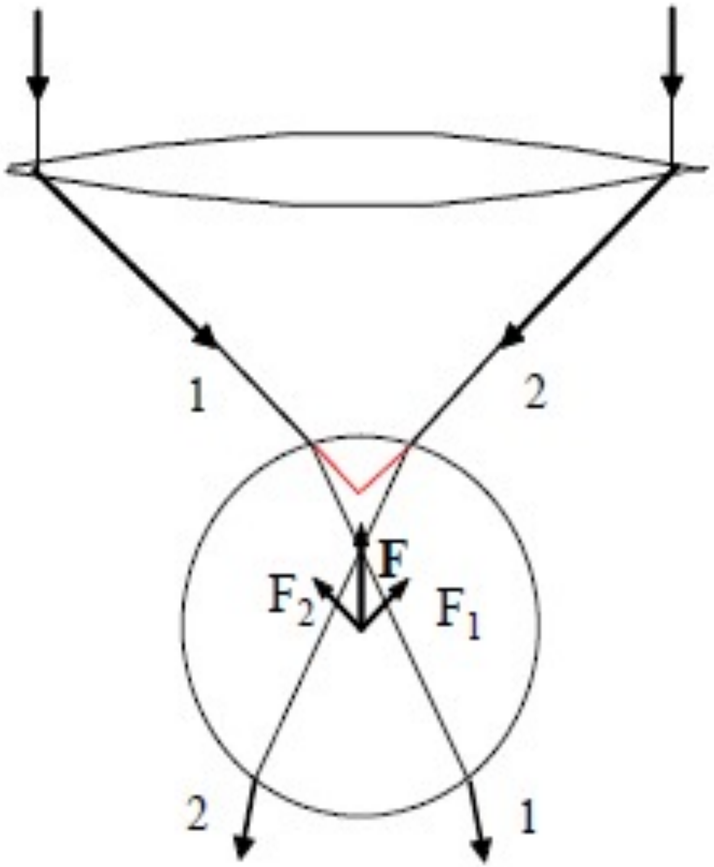


Figure 1. Schematic diagram showing the force on a dielectric sphere due to refraction of two rays of light, 1 and 2. The resultant force on the bead due to refraction is towards the focus.

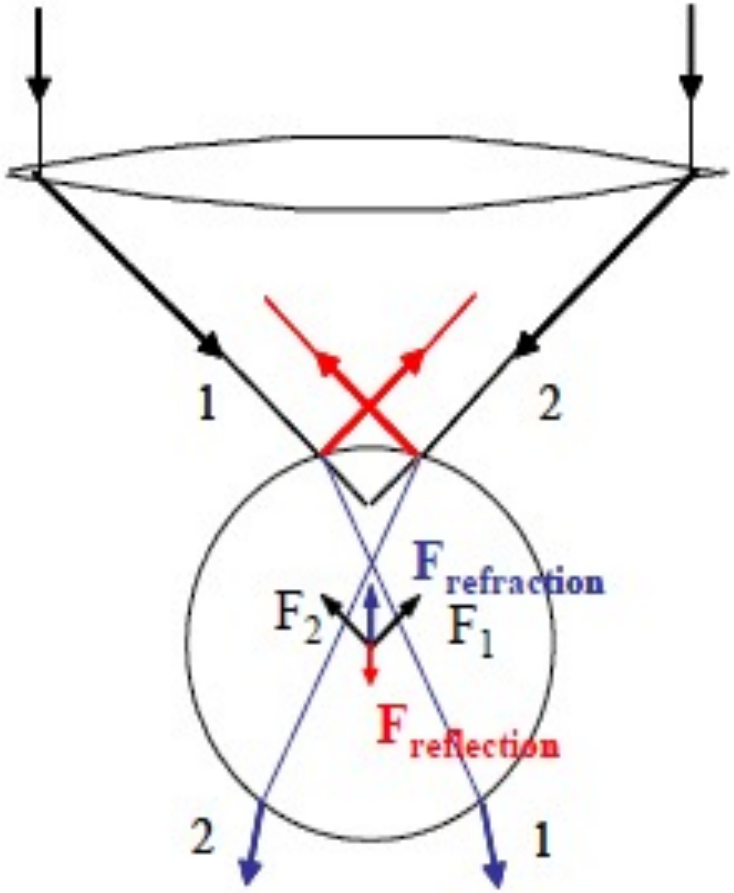


Figure 2. Schematic diagram showing the force on a dielectric sphere due to both reflection and refraction of two rays of light.

The Optical Tweezers

For dielectric particles in presence of a strongly focused beam the main contribution is coming from the electric field. Thus the total energy variation can be expressed as the dipole interaction:

$$U = -\int_V P_i E_{oi} \, dv$$

where $P_i = \epsilon_0 \chi E_{oi}$, E_{oi} is the incident field and $\chi = \epsilon - 1$. This reduce the dipole interaction energy to

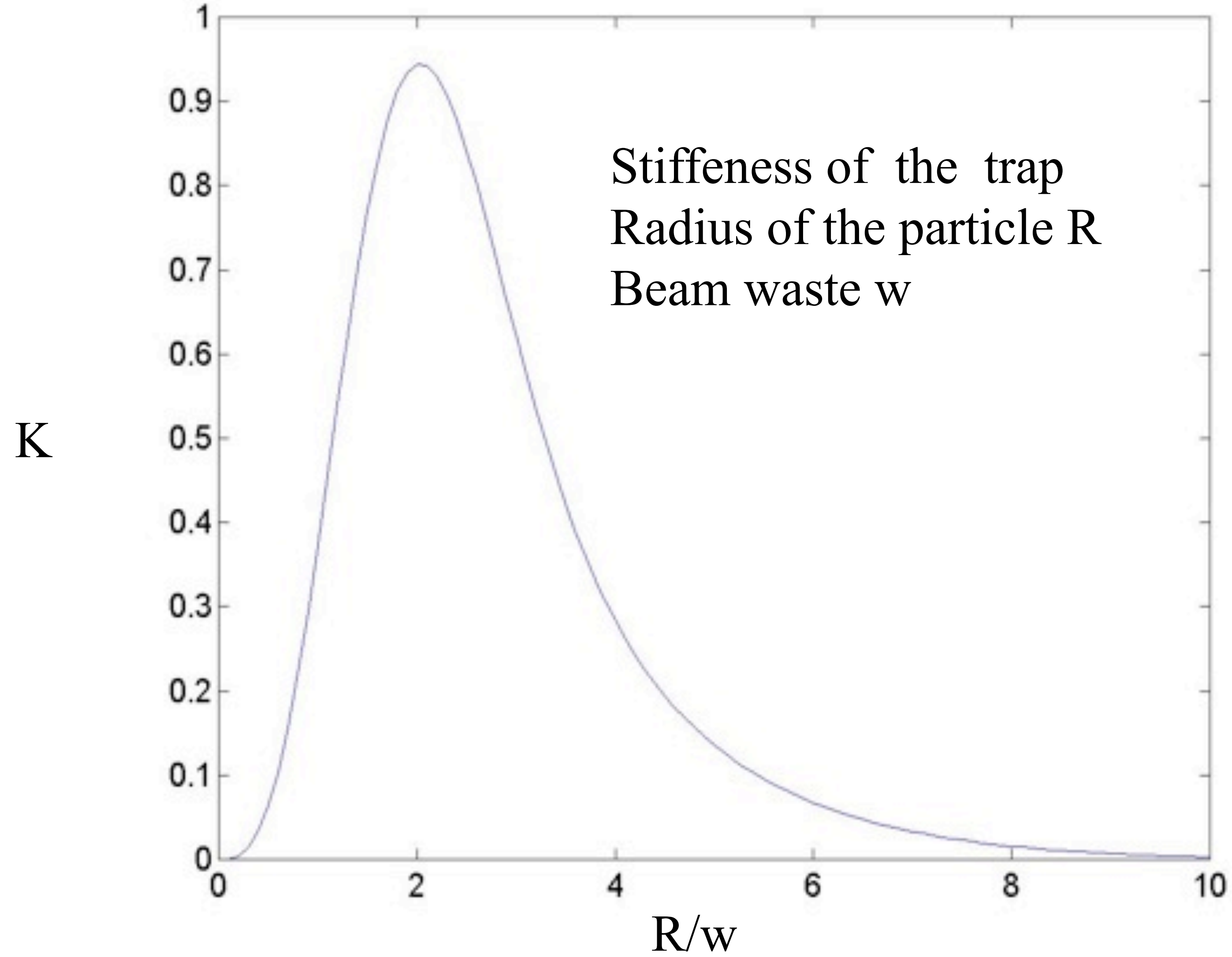
$$U = -\alpha \int_V I \, dv$$

where $I = \epsilon_f \epsilon_0 E_0^2$ is the intensity of the laser beam and $\alpha = \frac{\epsilon_p}{\epsilon_f} - 1 = \frac{n_p^2}{n_f^2} - 1$

ϵ_f and ϵ_p are the dielectric constant of the fluid and of the particle.

The Optical Tweezers

Then, the optical gradient force is simply given by the change of U in response to a change of the particles coordinates.



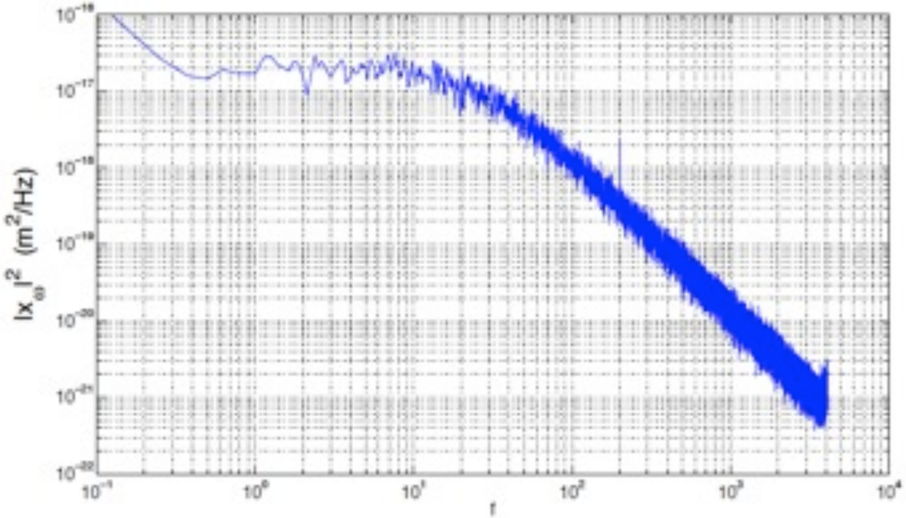


FIGURE 1 – Spectre de puissance de la position d'une particule piégée par un piège optique dans un fluide visqueux.

Question :
how can we calibrate the system ?

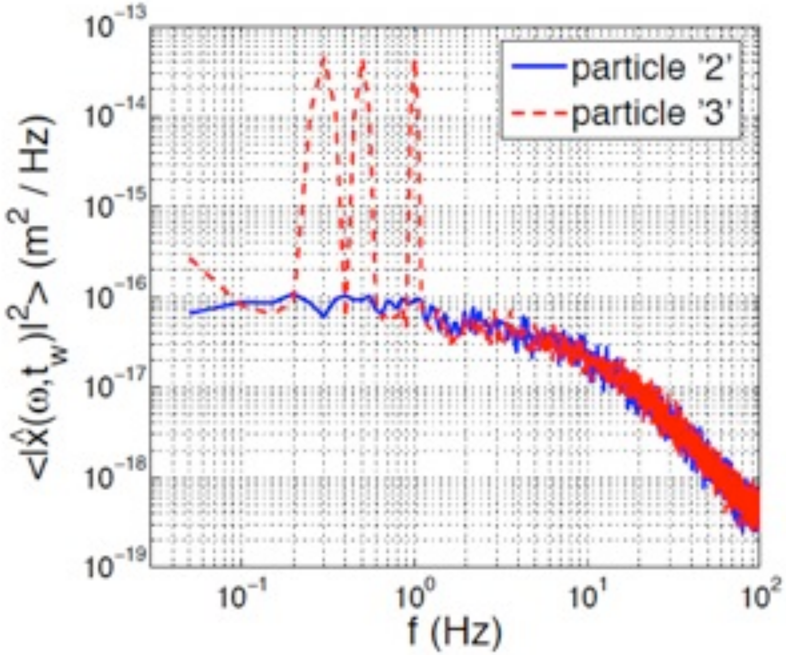
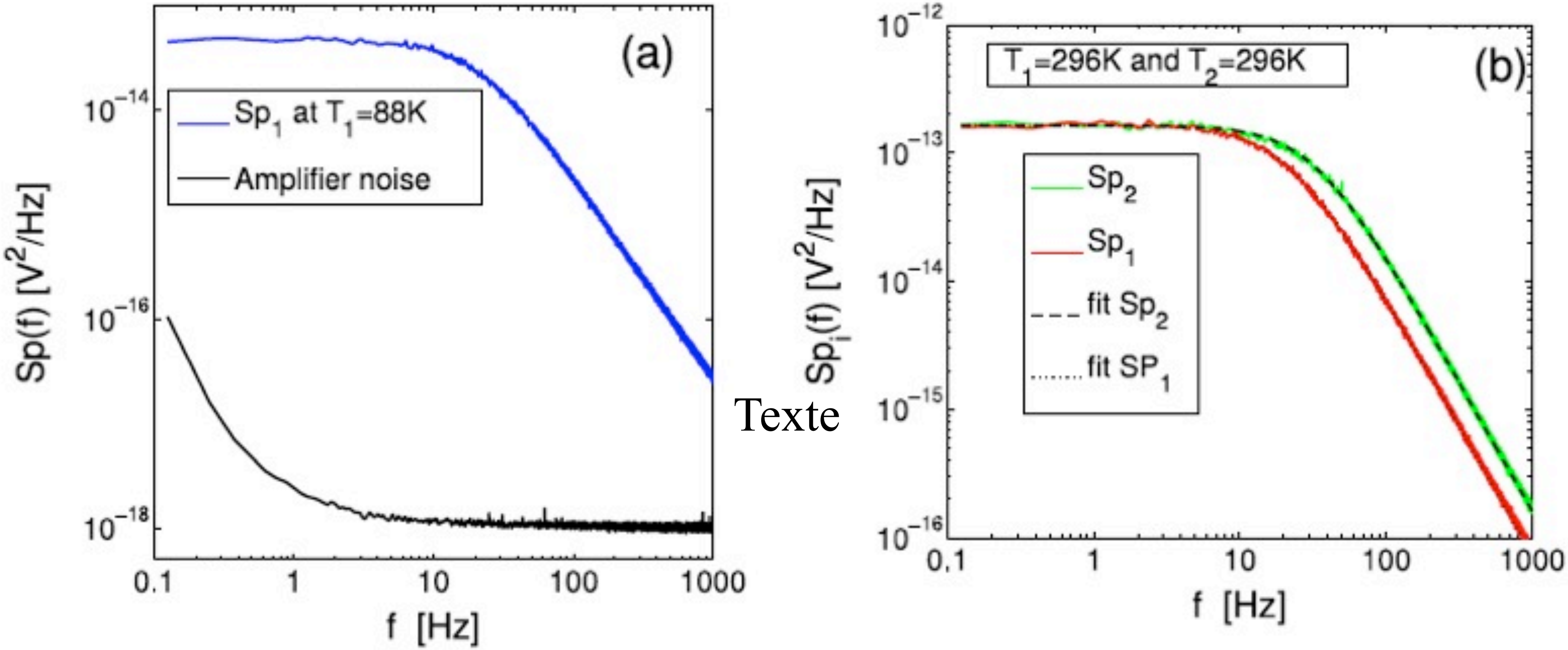


FIGURE 2 – Spectres de puissance de la position d'une particule piégée à l'équilibre et soumise à une force externe.

Spectra of the electric noise



Texte

Figure 2. (a) The power spectrum Sp_1 of V_1 measured at $T_1 = 88$ K (blue line) ($C = 100$ pF, $C_1 = 680$ pF, $C_2 = 430$ pF) is compared with the spectrum of the amplifier noise. (b) The equilibrium spectra Sp_1 (red line) and Sp_2 (green line) measured at $T_1 = T_2 = 296$ K are compared with predictions of equations (45) and (46) in order to check the values of the capacitances (C_1, C_2).