FLUCTUATIONS ENERGY HARVESTING WITH NONLINEAR OSCILLATORS

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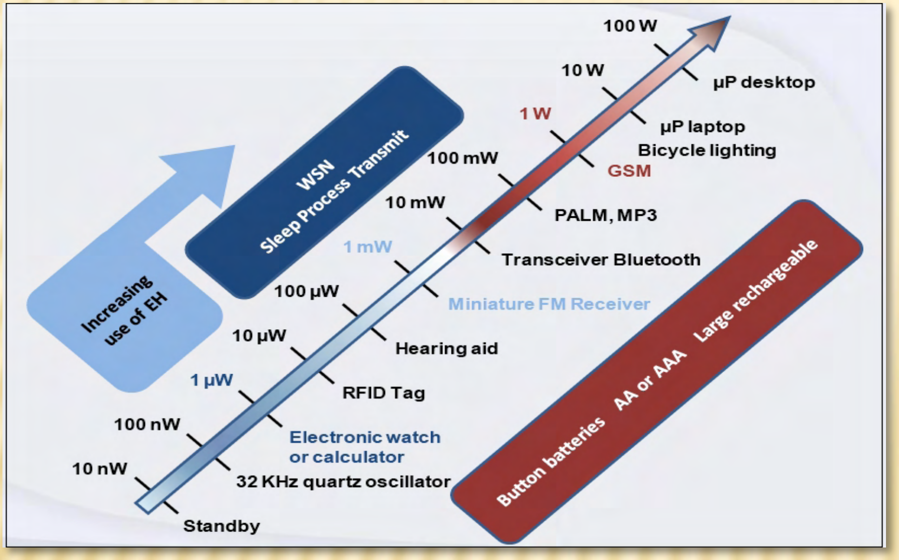
WISEPOWER

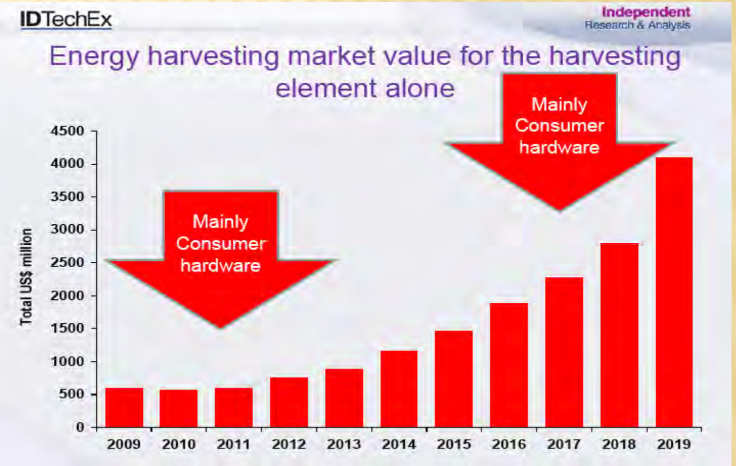
PLAN

- Why are we spending time with the subject of Energy Harvesting ?
- Why is Energy Harvesting so difficult ?
- What are fluctuations and how can we harvest them ?

Why are we spending time with the subject of Energy Harvesting ?

There is an increasing demand of portable power that is not satisfied by batteries…



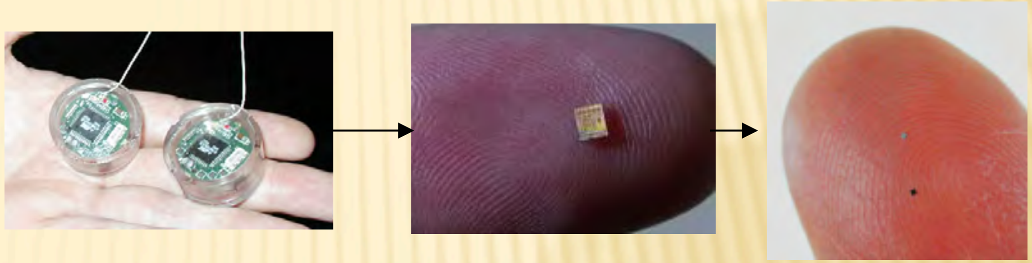


Estimated growth of the energy harvesting devices in the next ten years, in million USD. Source: IDTechEx, 2009.

Source: IDTechEx, "Energy Harvesting and Storage 2009-2019", Cambridge 2009.
EH: Energy Harvesting; WSN: Wireless Sensors Network

Wireless sensor networks

- Small (<1cm^3)
- Lightweight (<100 gr)
- **Low Power (<100 µW)**
- Long-lasting (2-10 yr)
- Inexpensive (<1 $)
- Low data rate
- wireless platforms
- Flexibility



Present
(cubic centimeter)

Future
(cubic sub-millimeter
sub-micrometer)

Monitoring and controlling different environments through a network of small, distributed, cheap, low consumption, adaptable, interconnected, smart devices represents a new important opportunity that is rapidly becoming a reality.

Problem: how to power them?

Different approaches:

1) Energy produced in one central place: battery-like
2) Energy produced when and where available (and locally stored)

Energy harvesting deals with the approach 2)

There is an increasing demand of portable power that is not satisfied by batteries…

Because they are un-practical:

-they need replacement when exhausted
-They need careful disposal
-They add to pollution
-They are bulky
-They cost money

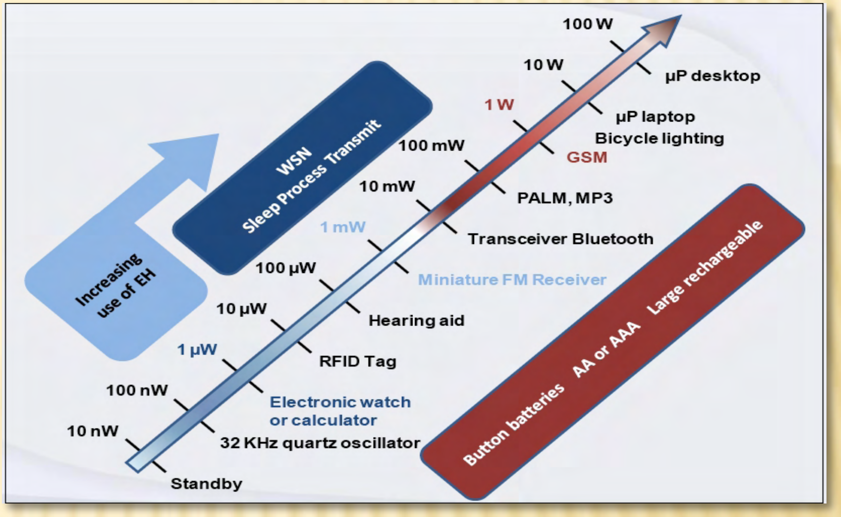
Because they are unavailable:

The goal is to realize **self-powered** nanoscale electronic devices.

From the solution of this problem major impact on Science, Technology, Economy and Society is expected

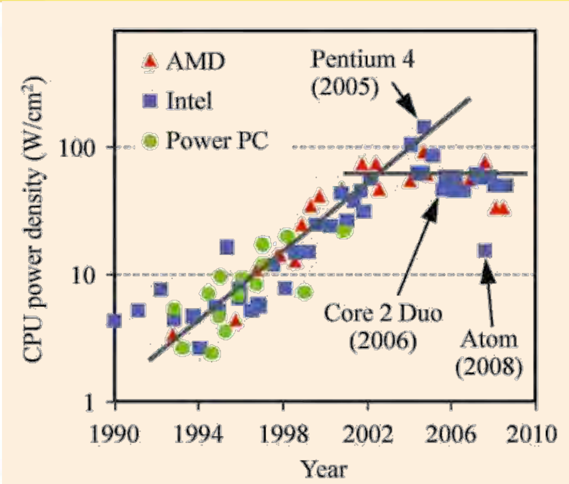
HOW TO TURN PROBLEMS…

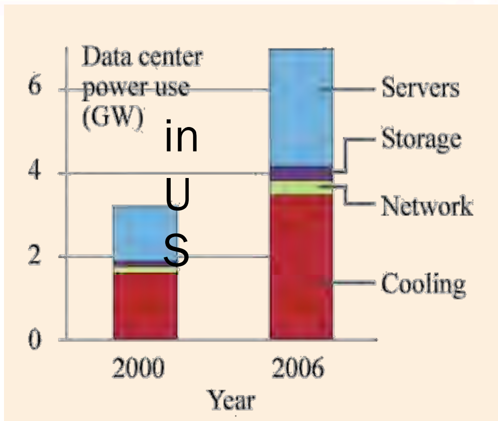
1) There is an increasing demand of portable energy for powering small electronic devices



Source: IDTechEx, "Energy Harvesting and Storage 2009-2019", Cambridge 2009.
EH: Energy Harvesting; WSN: Wireless Sensors Network

2) Energy efficiency in computing systems has become a major issue for the future of ICT





E. Pop, *Energy Dissipation and Transport in Nanoscale Devices*, Nano Res (2010) 3: 147–169

HOW TO TURN PROBLEMS… INTO AN OPPORTUNITY

What these two problems have in common?

They both sits on a common scientific ground:

Micro and nano scale energy management

Questions like:

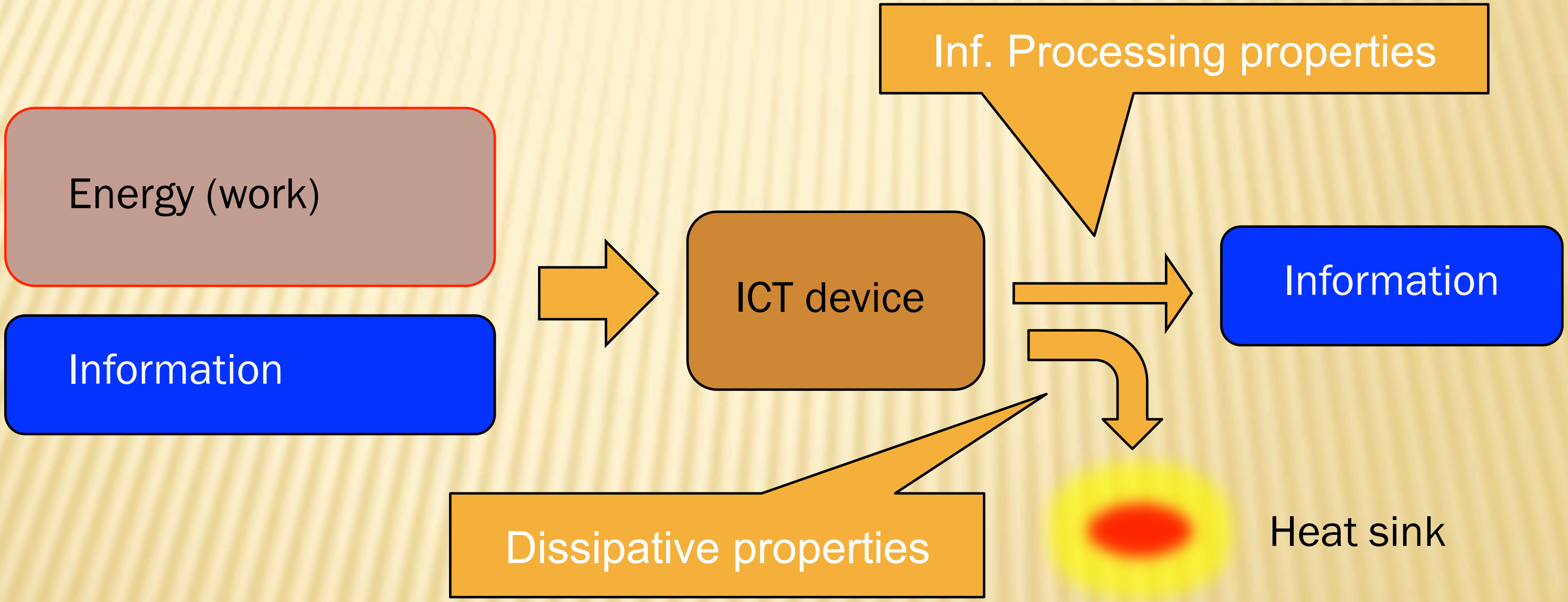
-How does electric energy get converted into heat at nanoscale
-How can we find an information transport solution that does not add to dissipation
-How can we harvest thermal vibrations to power nanoscale devices
-…

Could be asked and answered within this framwork.

In order to better contestualize the issue let's focus on a scheme for ICT devices…

HOW TO TURN PROBLEMS… INTO AN OPPORTUNITY

An ICT device is a machine that inputs information and energy (under the form of work), processes both and outputs information and energy (mostly under the form of heat).



Energy efficiency is usually defined as the percentage of energy input to a device that is consumed in useful work and not wasted as useless heat,

Energy efficiency / Dissipative properties

Presently:

the main effort is aimed at cooling down the heat produced during computation with specific attention to the charge transport on one hand and on the other hand on reducing the voltage operating levels up to the point of not compromising the error rate due to voltage fluctuations.

We propose:

to address the problem at a very fundamental level:

- what are the basic mechanisms behind the heat production?
- How can we take advantage of the fluctuations instead of avoiding them?
- How the physics of the heat and charge transport can be merged with the phonon engineering in order to advance the computing tasks?

It is not simply an incremental progress toward the reduction of heat production in room temperature conductors or new technology *beyond CMOS*.

It is a new, visionary approach that challenges the very basic foundation of thermodynamics. We propose to understand the dissipative mechanisms at nanoscale with the aim at setting the bases for a new thermodynamics of ICT devices.

Target Outcome / Expected Impact

The specific outcome of research in this area will cover the following results:

- the significant decrease of the power needed by the most common ICT devices
- an extension of the laws of thermodynamics to nanoscale systems
- a fundamental physics description of the processes related to heat dissipation
- the growth of a novel field related to phonon engineering for ICT applications
- the experimental realization of reversible logic gates
- the realization of *ICT in-body, ICT in-civil system and transport vehicles*

10

The expected impact in 10 years would be the growth of the bases for a new technology based on nanoscale devices that harness thermal fluctuations and process information with reduced power.

The energy efficiency issue: some more clues…

There are fundamental physics ISSUES that are relevant

1. Nanoscale thermodynamics *vs* macroscale thermodynamics

   Hill, Terrell, L., (2001). “Nanothermodynamics”, *Nanoletters,* 1, 111, 273

2. Non-equilibrium statistical mechanics *vs* standard statistical mechanics

3. Linear dynamics *vs* Nonlinear dynamics

At the nanoscale, in fact, thermal fluctuations, negligible at higher scale, become the most relevant factor and non-equilibrium thermodynamics approaches are required as opposed to the traditional concepts based on equilibrium energy balances. *Non-equilibrium work relations,* mainly in the form of “fluctuation theorems”, have shown to provide valuable information on the role of *non-equilibrium* fluctuations.

- Bustamante, C., Liphardt, J. and Ritort, F., *The nonequilibrium thermodynamics of small systems*, PHYSICS TODAY, 2005, 58, p.43-48.
- F. Ritort, *Work fluctuations, transient violations of the second law and free-energy recovery methods: Perspectives in Theory and Experiments*, Poincare Sem. 2 (2003) 193.
- Gallavotti G., Cohen E.G.D., *Dynamical ensembles in nonequilibrium statistical mechanics*, Phys Rev Lett, 2694 (1995).

ON A BROADER PERSPECTIVE

The well-known laws of heat and work transformation that lie at the base of the classical thermodynamics are going to need a rethinking. The very basic mechanism behind energy dissipation requires a new definition when non-equilibrium processes involving only few degrees of freedom are considered.

Industrial Revolution XVIII-XIX	ICT Revolution XX-XXI
Heat-Work relations	Fluctuation-Dissipation relations
	Information is physical !!!

CHALLENGE:

the description of **energy transformation processes at the nanoscale** aimed at unveiling new mechanisms for powering next generations of ICT devices.

RESEARCH AGENDA

To address this challenge a multidisciplinary approach is required.

Dissipation proc. & *non-equilibrium relaxation in solid-state*

Theor. Physics

A new understanding of ***charge and heat tra*** ***…terials***

Material Science

Relation between information and ene…

Comp. Science

Energy proc. in **Brow…** **…d bio-inspired** energy transf.

Bio/Eng

Noise operated l… ***…stochastic computing***

Comp. Scie… …ath

…basic elements to implement the ICT functions

Enginering

Non-Equilibrium NanoThermodynamics

Impact

The impact is hardly overestimated

Basic science: Advances in nano-scale energy-conversion mechanisms.

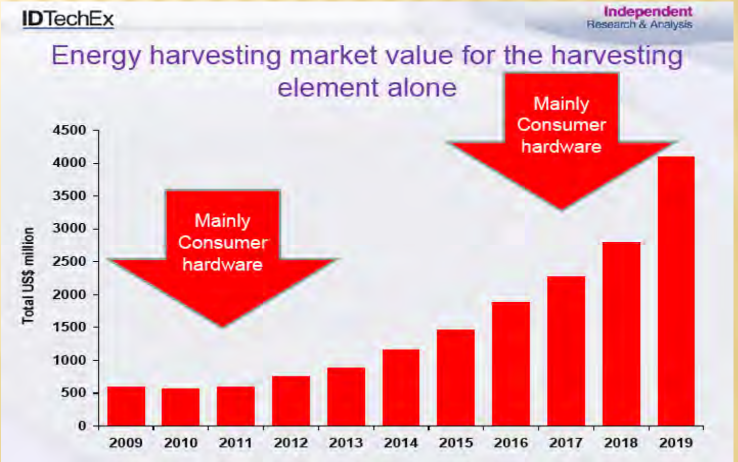
Advances in nonlinear stochastic dynamics: the usual vibration-to-electricity conversion mechanisms are based on linear oscillators tuned to the frequency of vibration sources. New approaches could take advantage of nonlinear dynamics to improve the **efficiency** of the conversion mechanism.

Technology

The availability of onboard power generators will open up the possibility of building nano-scale devices (from sensors/ actuators to computing/communicating) with application in a vast number of fields. ICT technology can be seriously affected by such possibility.

Economy:

The impact on the economy of ICT can be very relevant. A new class of devices, up to now only dreamt of, could be made available for practical applications.



Estimated growth of the energy harvesting devices in the next ten years, in million USD. Source: IDTechEx, 2009.

Impact
The impact is hardly overestimated

Society:

The impact on society can be extremely relevant for a number of fields.
Among these:

- wireless communications and social behaviours,
- human health remote monitoring and control,
- remote sensing,
- environmental control,
- privacy and security,
- …

The topic is of interest for different **research communities**:

- the *nanotechnology* comm. interested in new information oriented devices.
- *computer science community (wireless sensor networks)*
- *nonlinear stochastic dynamics* community
- the *electronic eng. devoted to powering solutions* design
- …

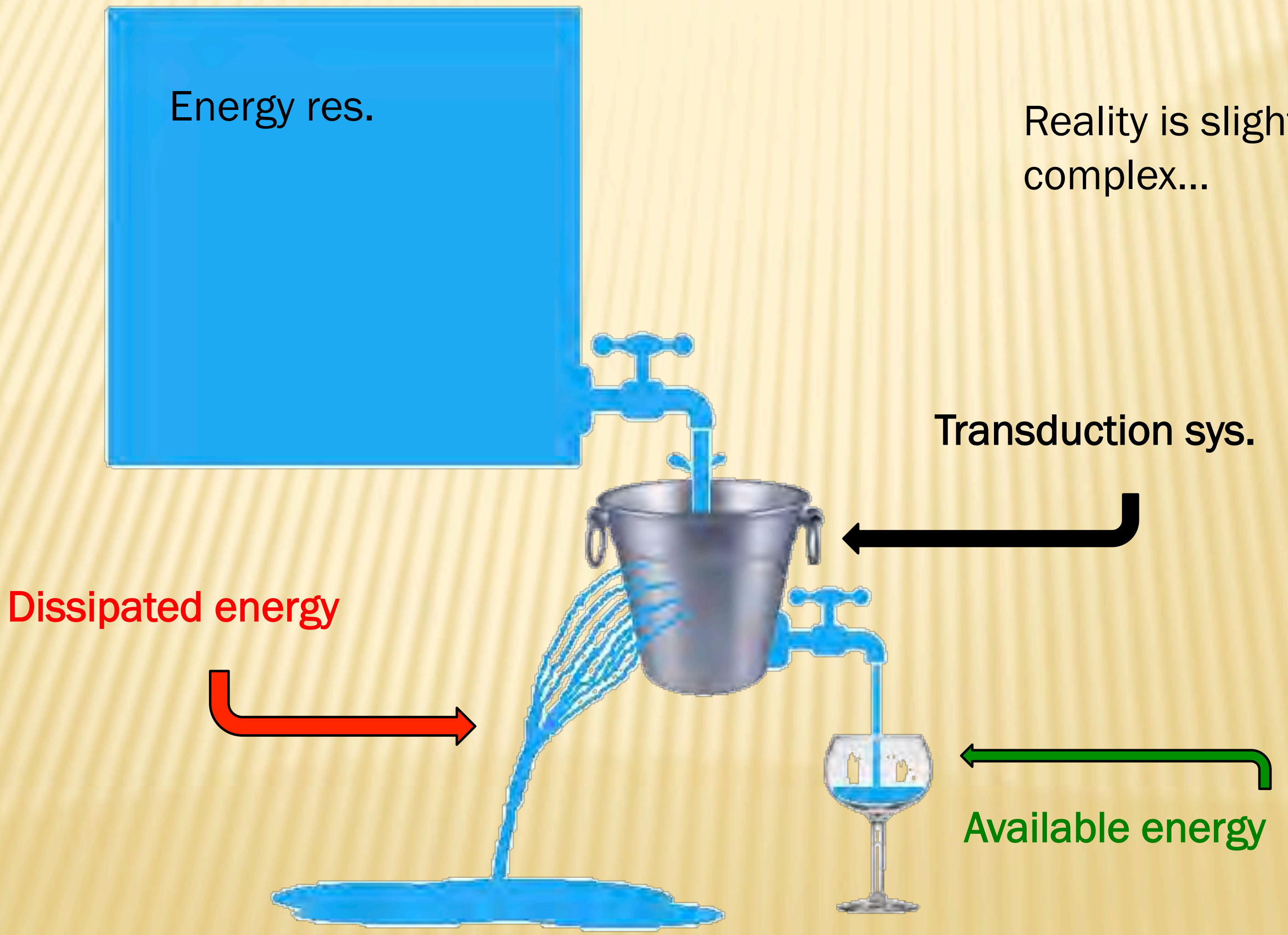
What is Energy Harvesting ?

ENERGY HARVESTING BASIC IDEAS

Unlimited source of free energy, readily available for multiple uses...

ENERGY HARVESTING BASIC IDEAS

Reality is slightly more complex...



ENERGY HARVESTING BASIC IDEAS

Kinetic energy

wind

sound

Falling bodies

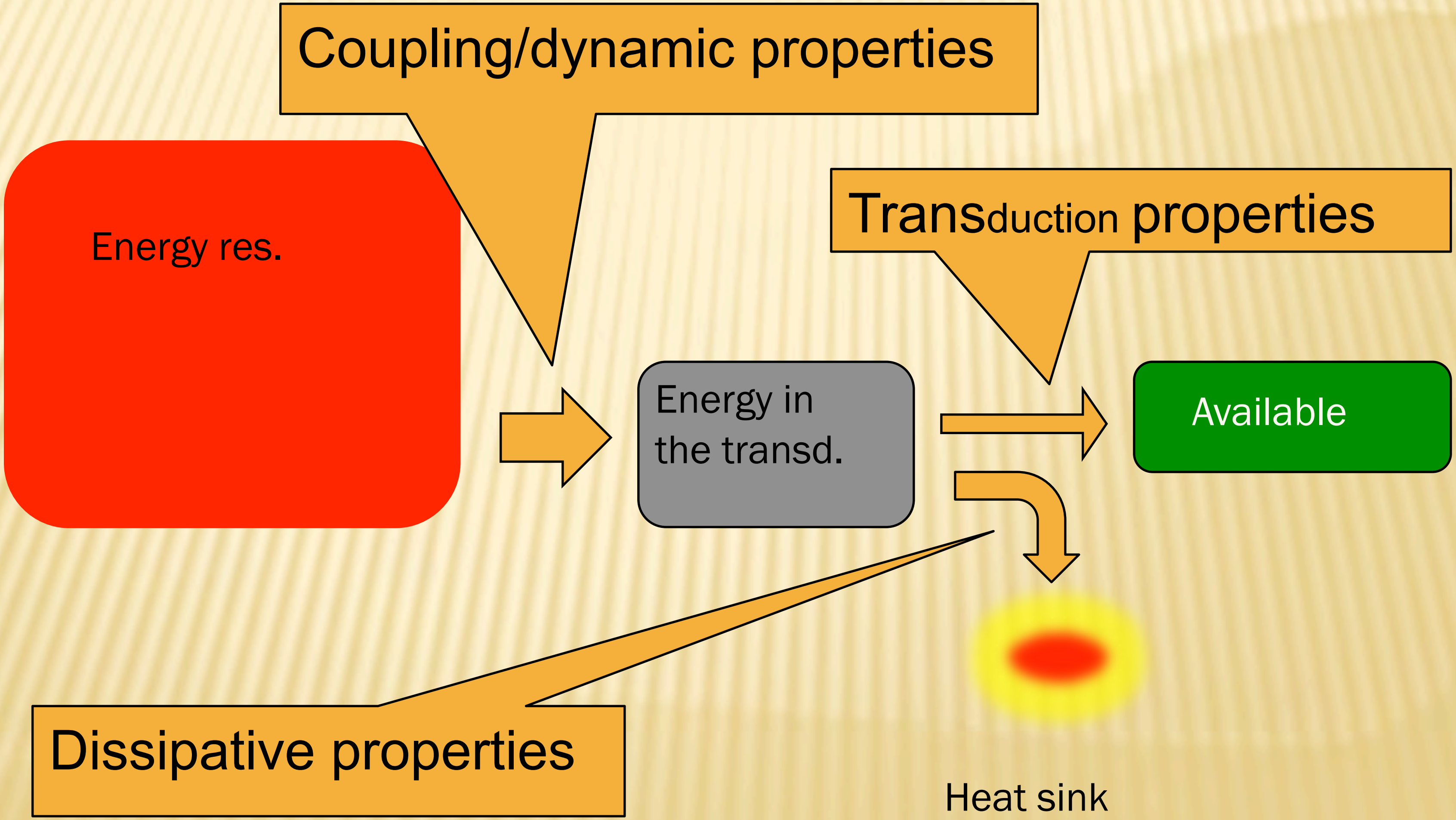
vibrations

water waves and tides

Focus on vibrations of solid bodies....

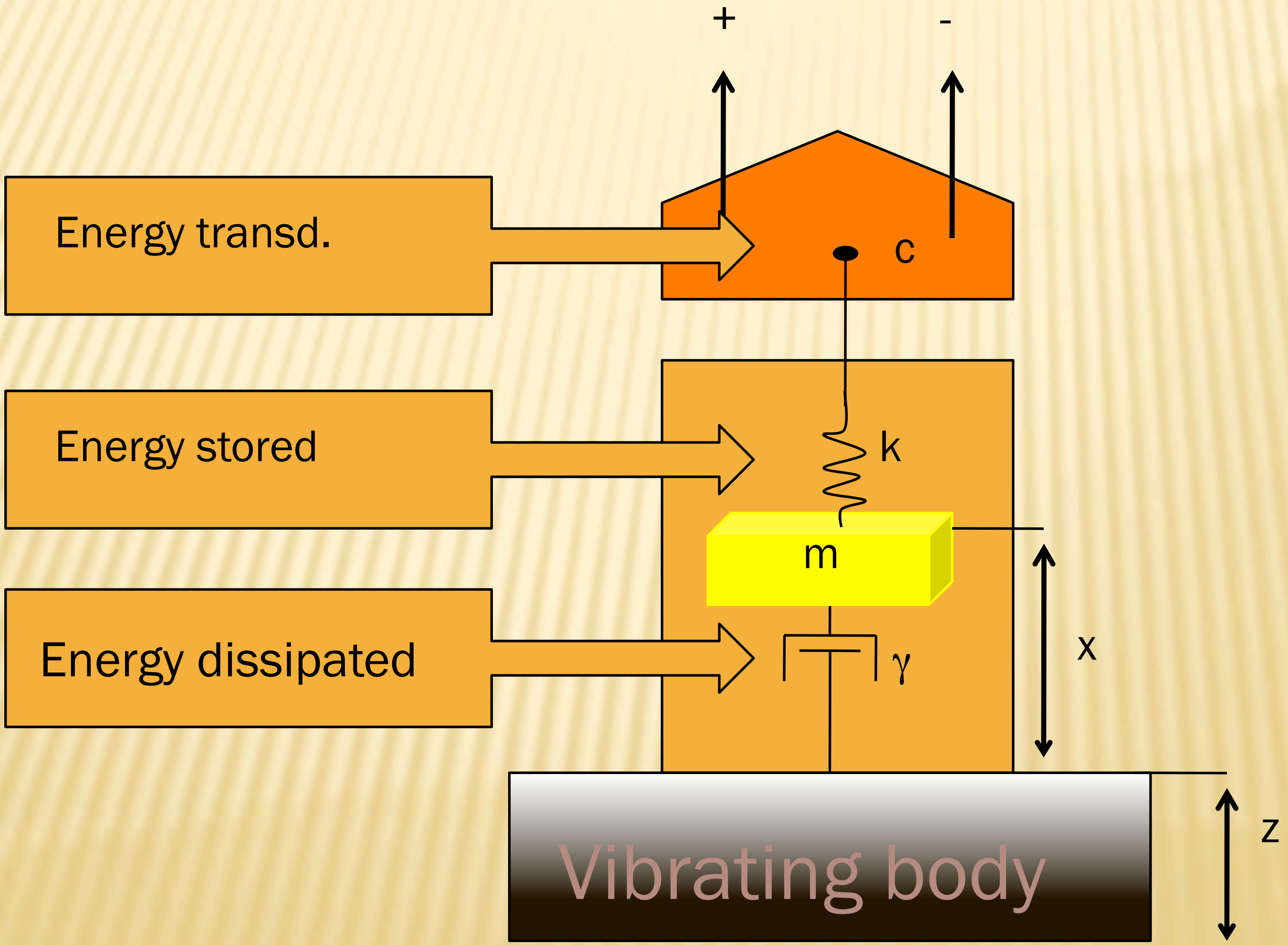
VIBRATIONS ENERGY HARVESTING

Energy budget

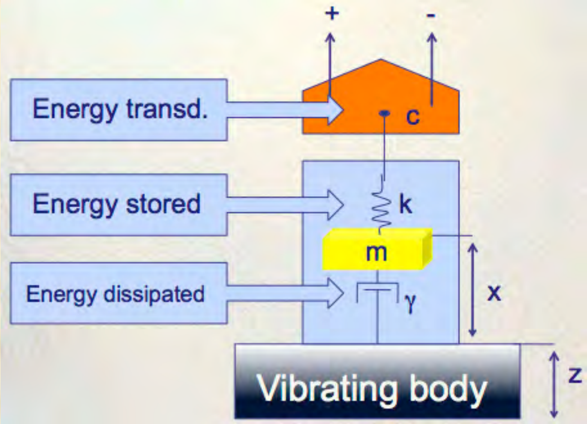


VIBRATIONS ENERGY HARVESTING

Dynamical model



VIBRATIONS ENERGY HARVESTING



Dynamical model

$$m\ddot{x} = -\frac{dU(x)}{dx} - \gamma\dot{x} - c(x,V) + \zeta_z$$

Where:

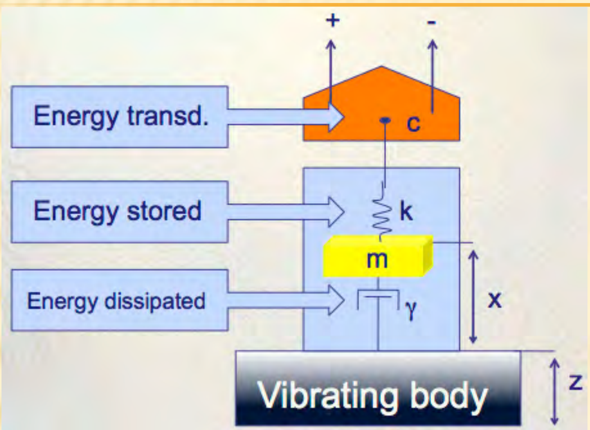
$U(x)$ Represents the Energy stored

$\gamma\dot{x}$ Accounts for the Energy dissipated

$c(x,V)$ Accounts for the Energy transduced

ζ_z Accounts for the input Energy

VIBRATIONS ENERGY HARVESTING

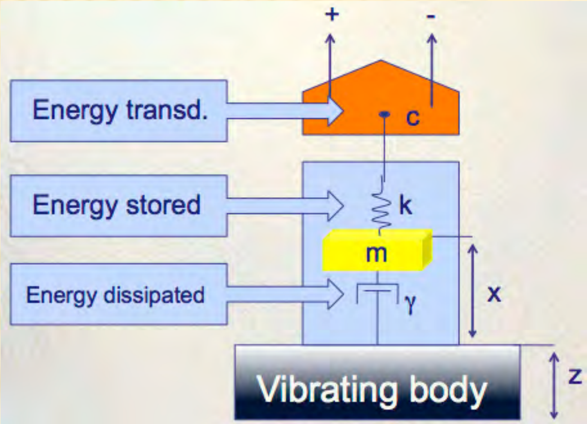


Dynamical model

$$\begin{cases} m\ddot{x} = -\dfrac{dU(x)}{dx} - \gamma\dot{x} - c(x,V) + \zeta_z \\ \dot{V} = F(\dot{x},V) \end{cases}$$

Equations that link the vibration-induced displacement with the Voltage

VIBRATIONS ENERGY HARVESTING



Dynamical model

Equations that link the vibration-induced displacement with the Voltage

$$\begin{cases} m\ddot{x} = -\dfrac{dU(x)}{dx} - \gamma\dot{x} - c(x,V) + \zeta_z \\ \dot{V} = F(\dot{x},V) \end{cases}$$

Details depend on the physics of the conversion principles...

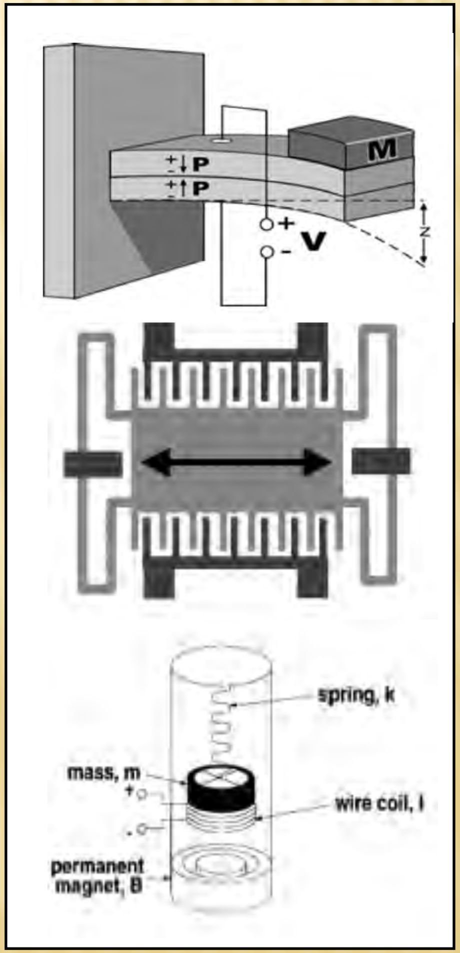
VIBRATIONS ENERGY HARVESTING

Transduction mechanisms

1. Piezoelectric: dynamical strain is converted into voltage difference.

2. Capacitive: geometrical variations induce voltage difference

3. Inductive: dynamical oscillations of magnets induce electric current in coils



VIBRATIONS ENERGY HARVESTING

1 Piezoelectric: dynamical strain is converted into voltage difference.

$$
\begin{cases}
m\ddot{x} = -\dfrac{dU(x)}{dx} - \gamma\dot{x} - K_V V + \xi_z \\[2ex]
\dot{V} = K_c \dot{x} - \dfrac{1}{\tau_p} V
\end{cases}
$$

The available power is proportional to V^2

VIBRATIONS ENERGY HARVESTING

1 Piezoelectric: dynamical strain is converted into voltage difference.

$$\begin{cases} m\ddot{x} = -\dfrac{dU(x)}{dx} - \gamma\dot{x} - K_V V + \zeta_z \\ \dot{V} = K_c \dot{x} - \dfrac{1}{\tau_p} V \end{cases}$$

The Physics of piezo materials

K_c and K_v depends on **materials**

VIBRATIONS ENERGY HARVESTING

1 Piezoelectric: dynamical strain is converted into voltage difference.

$$\begin{cases} m\ddot{x} = -\dfrac{dU(x)}{dx} - \gamma\dot{x} - K_V V + \zeta_z \\ \dot{V} = K_c\dot{x} - \dfrac{1}{\tau_p} V \end{cases}$$

The oscillator dynamics

U(x) is the “elastic” potential mechanical energy of the oscillator

VIBRATIONS ENERGY HARVESTING

1 Piezoelectric: dynamical strain is converted into voltage difference.

$$\begin{cases} m\ddot{x} = -\dfrac{dU(x)}{dx} - \gamma\dot{x} - K_V V + \zeta_z \\ \dot{V} = K_c \dot{x} - \dfrac{1}{\tau_p} V \end{cases}$$

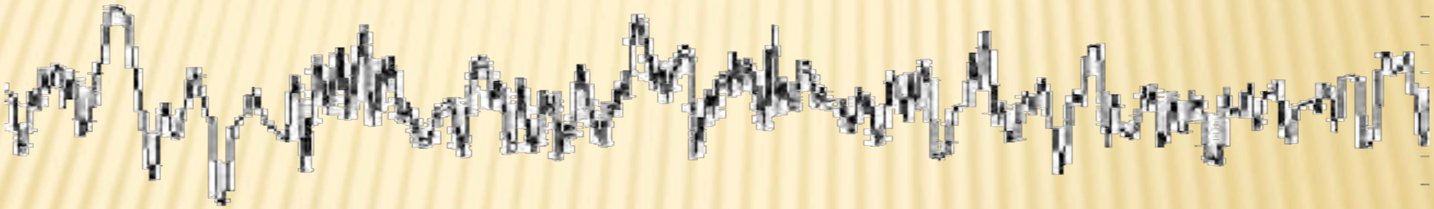
The environmental energy available

What are fluctuations and how can we harvest them ?

THE RANDOM CHARACTER OF KINETIC ENERGY

ζ_z Represents the vibration (force)

What does it look like?



At the micro-to-nano scales most of the energy available is **kinetic energy** present in the form of **random fluctuations**, i.e. **noise**.

Thus the challenge is to:

use the noise to power nano-scale devices aimed at Sensing/computing/acting and communicating.

THE RANDOM CHARACTER OF KINETIC ENERGY

Random vibrations / noise

Thermal noise
Acoustic noise
Seismic noise
Ambient noise (wind, pressure fluctuations, …)
Man made vibrations (human motion, machine vibrations,…)

All different for intensity, spectrum, statistics

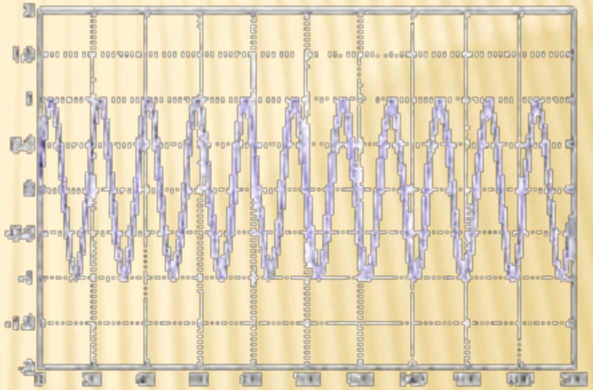
What do we mean with noise ?

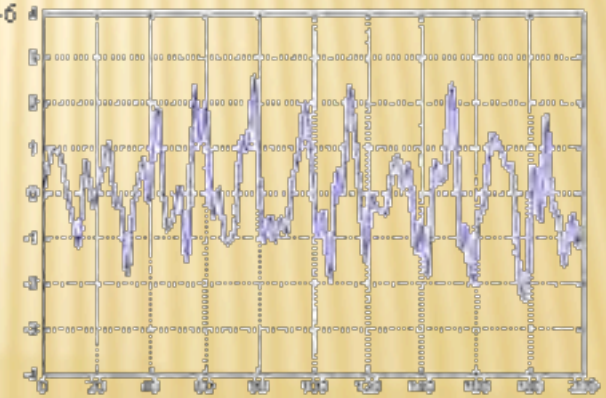
Noise in Physics means:
A disturbance, especially a random and persistent disturbance, that obscures or reduces the clarity of a signal.

Noise becomes relevant when we try to measure a physical quantity with high precision

"**Precision** is the ability of an instrument to produce the same value or result, given the same input"

Example: the measurement of the pendulum position





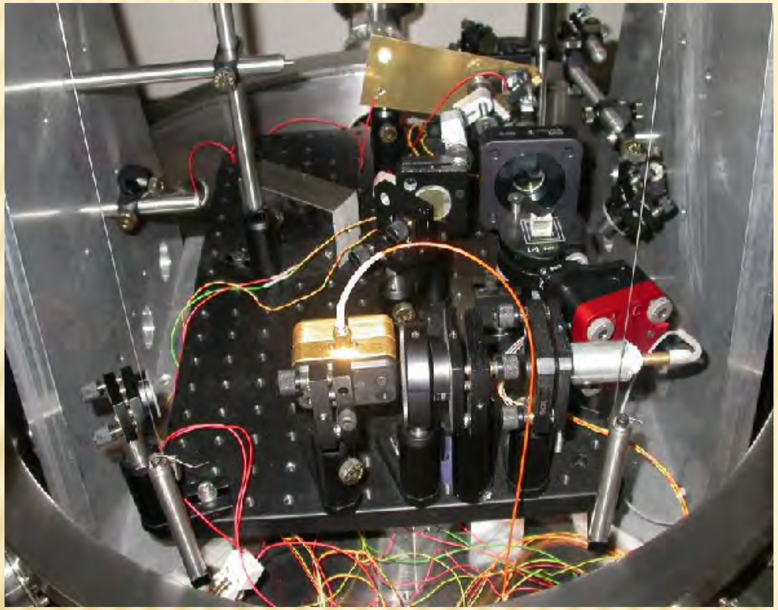
Example: the real measurement of a free swinging pendulum

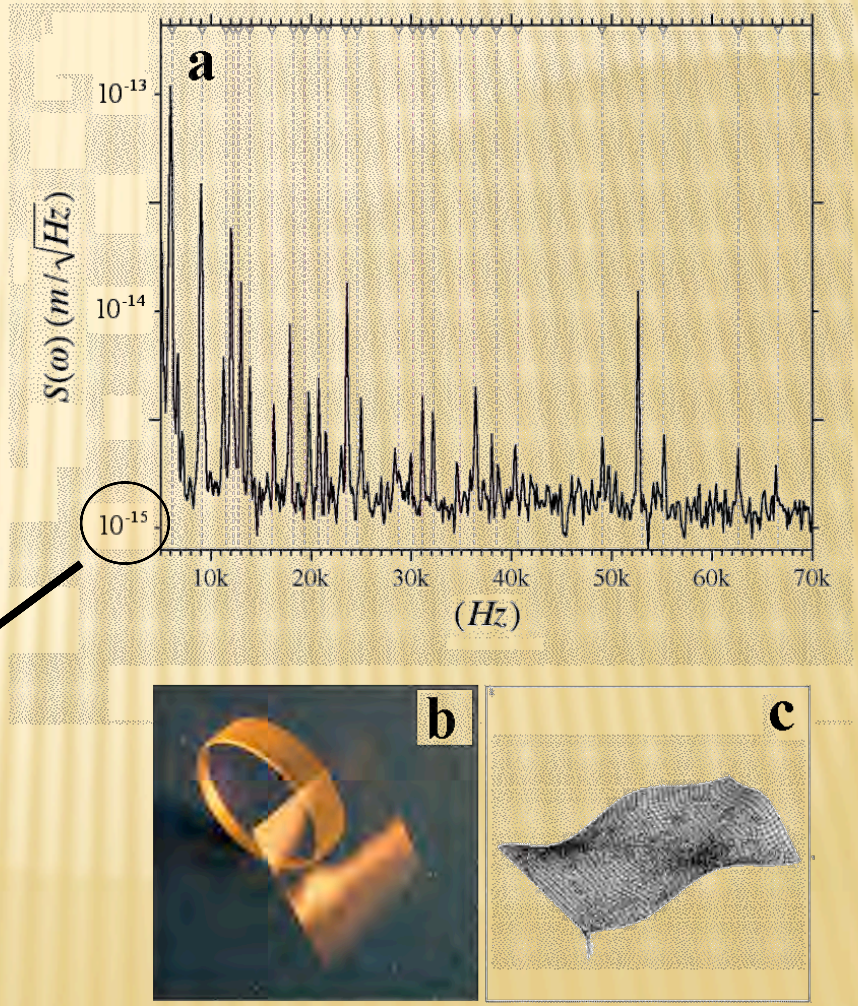
Mass m= 1 Kg
Length l = 1 m
rms motion = 2 10^{-11} m

Mass m= 1 g
Length l = 1 m
rms motion = 6 10^{-10} m

Mass m= 10^{-6} g
Length l = 1 m
rms motion approx 1 mircon

DIRECT MEASUREMENT OF INTERNAL VIBRATION ON A THIN FUSED SILICA SLAB

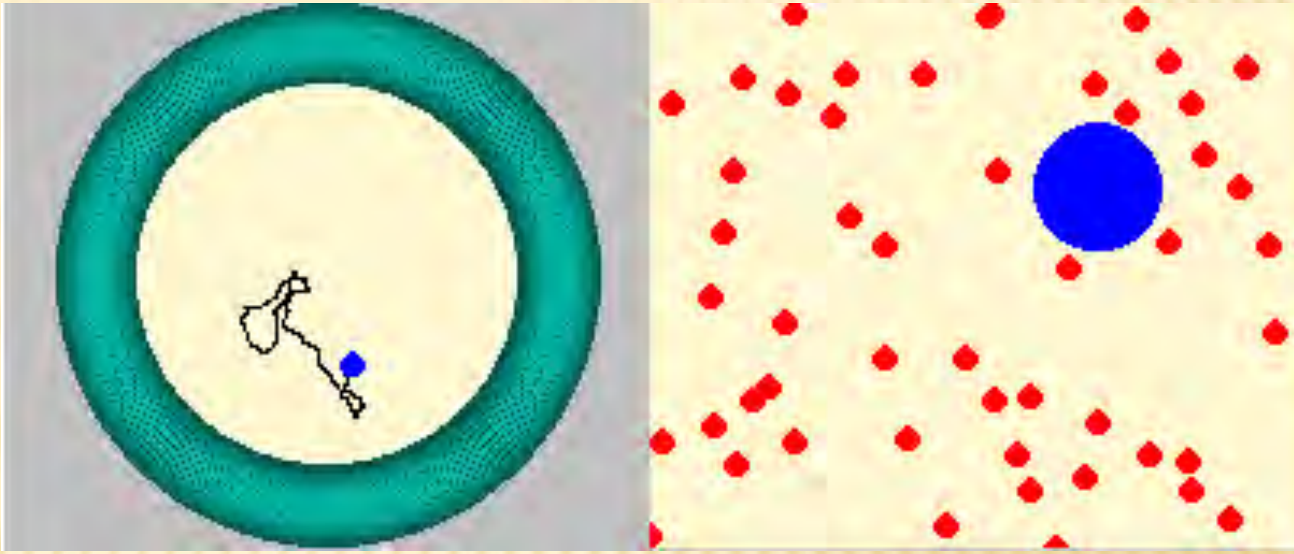




10^{-15}

Where all these fluctuations come from?

1828 R. Brown
1905 A. Einstein



Brownian motion → thermal noise

thermal noise is the name commonly given to **fluctuations** affecting a physical observable of a macroscopic system at thermal equilibrium with its environment.

The internal energy of a macroscopic apparatus at thermal equilibrium is shared between all its degrees of freedom or, equivalently, between all its normal modes each carrying an average energy kT, where T is the equilibrium temperature.

This is true also for such modes as the oscillations of springs, pendula, needles, etc.

Such an energy manifests itself as a random fluctuation of the relevant observable experimentally perceived as the noise affecting its measured value.

How to model thermal noise

To describe such a dynamics it is necessary to introduce a statistical approach:

a) Fokker-Plank equation

b) Langevin Equation

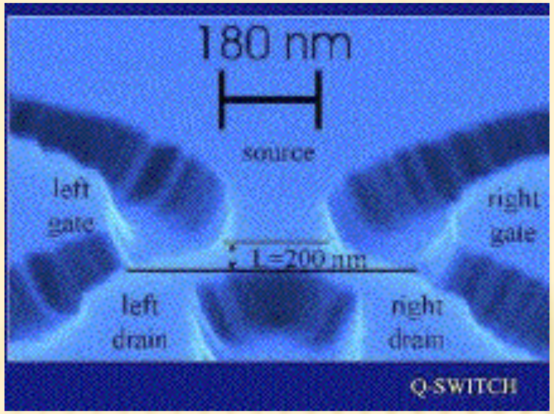
Important result → The **Fluctuation-Dissipation** theorem

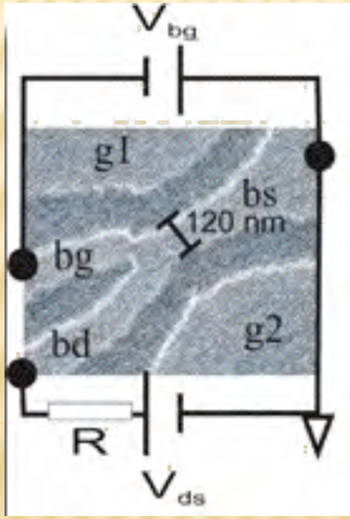
The dissipative properties of the dynamical system are directly related to the equilibrium fluctuations.

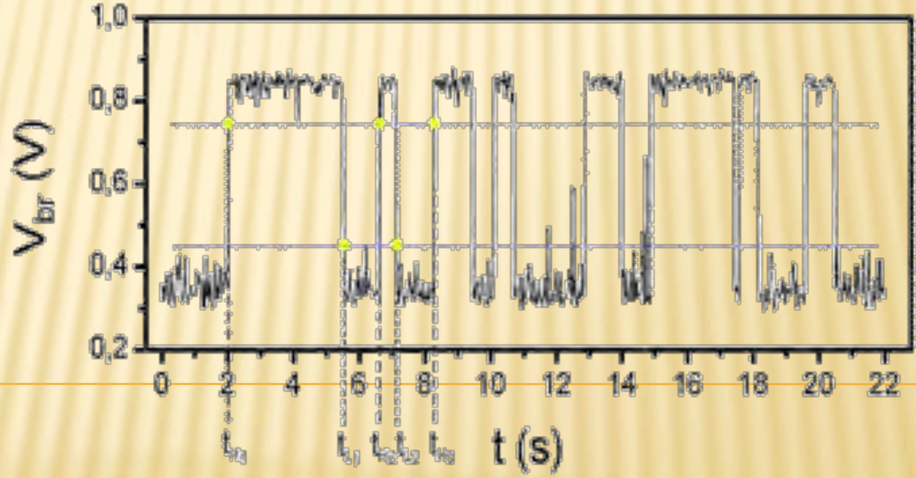
Physical connection:

the source of the fluctuations is the very same of the source of the dissipation

NANO SYSTEMS AFFECTED BY NOISE



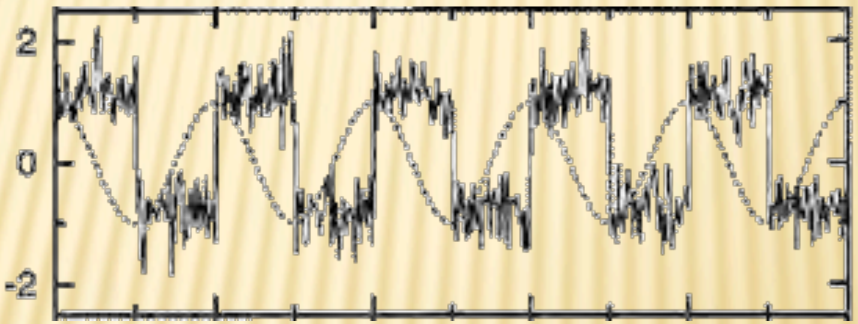




See **SUBTLE**: SUB KT Transistors and Sensors, FPVI FET http://subtle.fisica.unipg.it/

New paradigma for the role of noise.

The role of noise has been promoted from simple disturb to potentially fruitful resource, due to progresses in nonlinear stochastic dynamics. Phenomena like "**Stochastic Resonance**" and "**thermal ratchets**" have popularized the idea that noise can be exploited to produce improvements in system performances.



THE STOCHASTIC RESONANCE PHENOMENON

First paper in 1981 by Benzi, Parisi, Sutera, Vulpiani.
Since then more than 4000 papers (to date)…

For a review:
Stochastic Resonance, L. Gammaitoni, P. Hanggi, P. Jung, F. Marchesoni, Rev. Mod. Phys. 70, 223 (1998)

Stochastic Resonance

1998SR2008

Perugia, Aug. 17-21, 2008

THE CONFERENCE

The European Physical Journal B

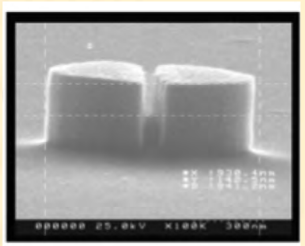
Vol. 69 No. 1 (May I 2009)

Special Issue: Stochastic Resonance

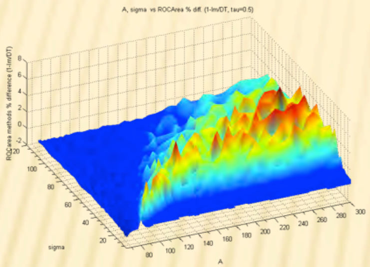
For further info see: www.stochastic-resonance.org

Putting thermal fluctuations at work

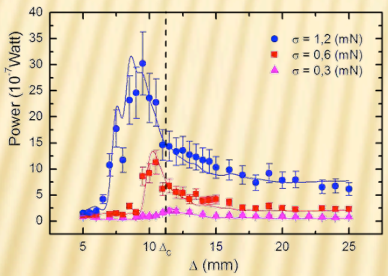
Few examples from the agenda…



1 Noise tollerant logic gates



2 Noise driven sensors



3 Random vibrations energy harvesting

4 Brownian motors

PLAN

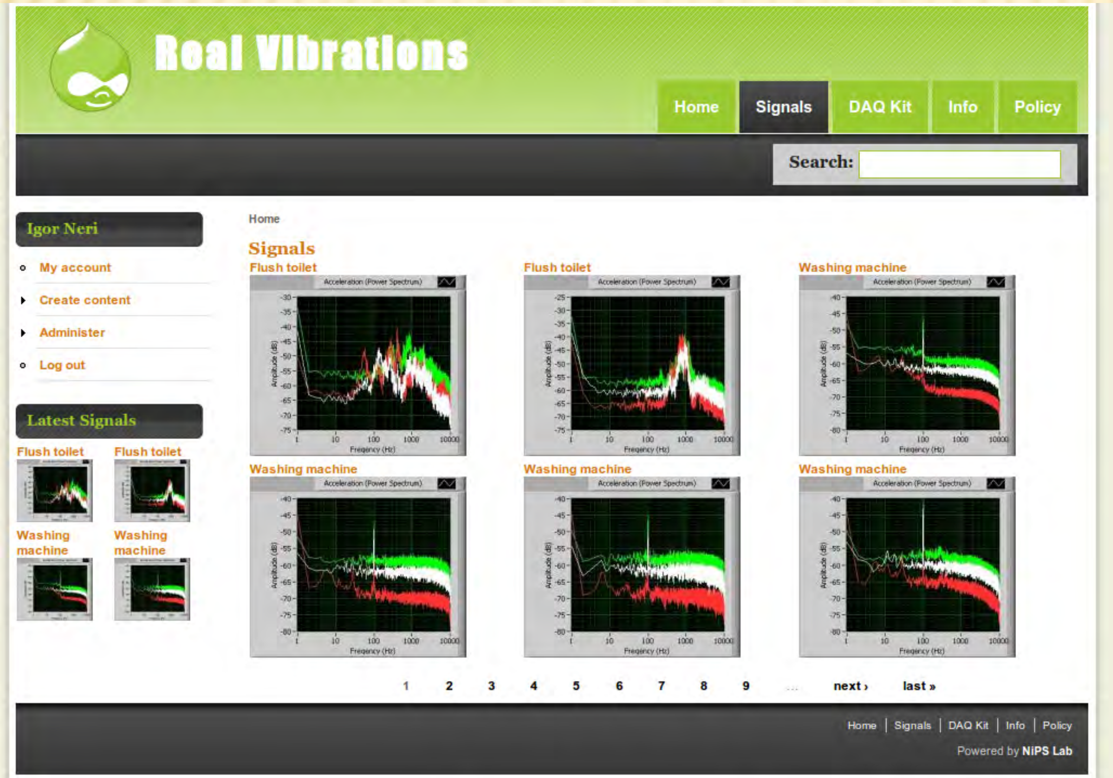
- Why are we spending time with the subject of Energy Harvesting ?
- What is Energy Harvesting ?
- What are fluctuations and how can we harvest them ?

THE RANDOM CHARACTER OF KINETIC ENERGY

It is very important that we can characterize the spectral features of the vibration we want to harvest…

Vibration sources digital library

This Task is devoted to the realization of database containing digital time series and spectral representations of experimentally acquired vibration signals.



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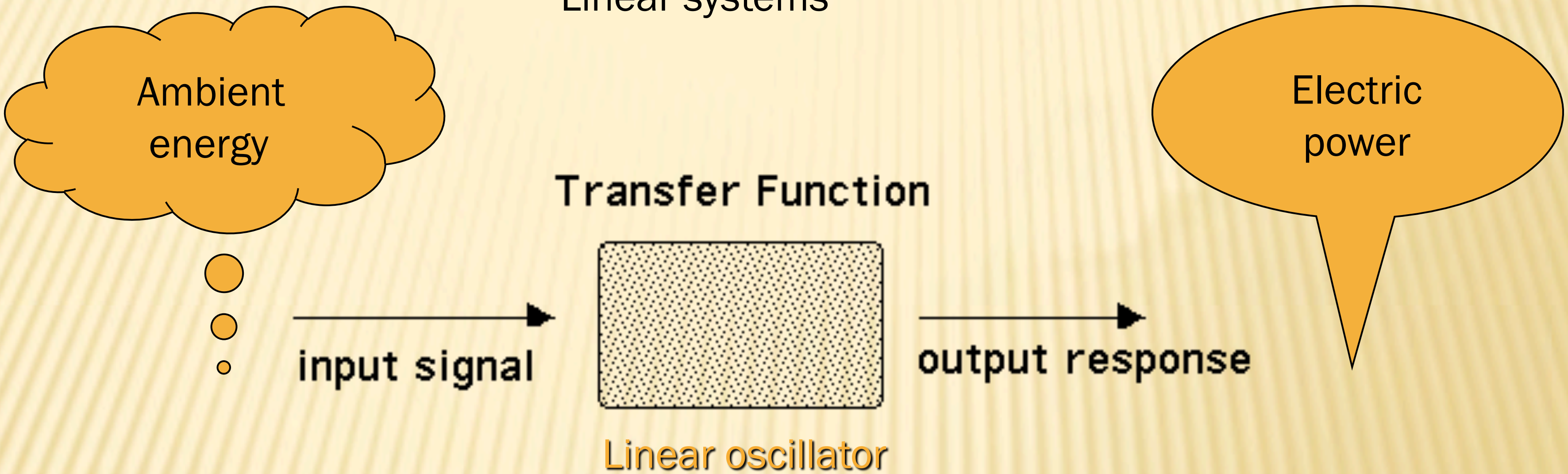
Signal presentation:
- Description
- Power spectrum
- Statistical data
- Time series download (authorized users)

VIBRATIONS ENERGY HARVESTING

Linear systems



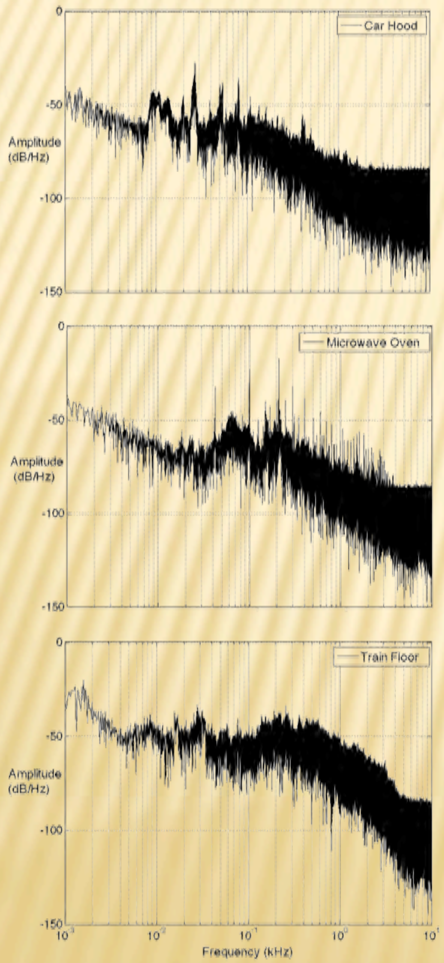
The transfer function is a math function of the frequency, in the complex domain, that can be used to represent the performance of a linear system

For a linear system the transfer function presents one or more peeks corresponding to the resonace frequencies and thus it is efficient mainly when the incoming energy is abundant in that regions…

This is a serious limitation when you want to build a small energy harvesting system…

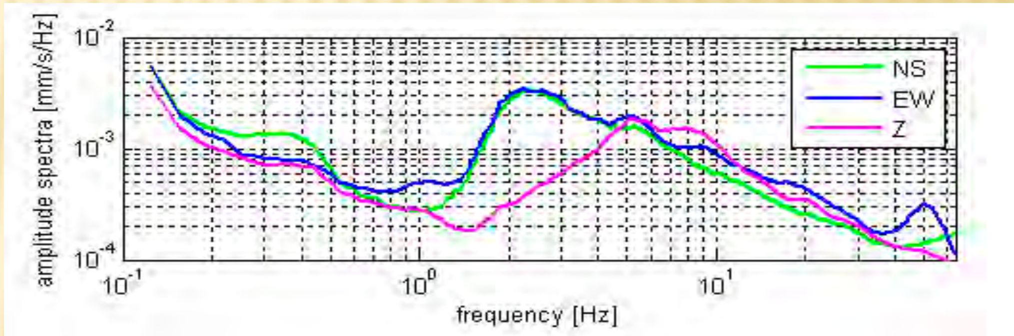
VIBRATIONS ENERGY HARVESTING

For two main reasons…

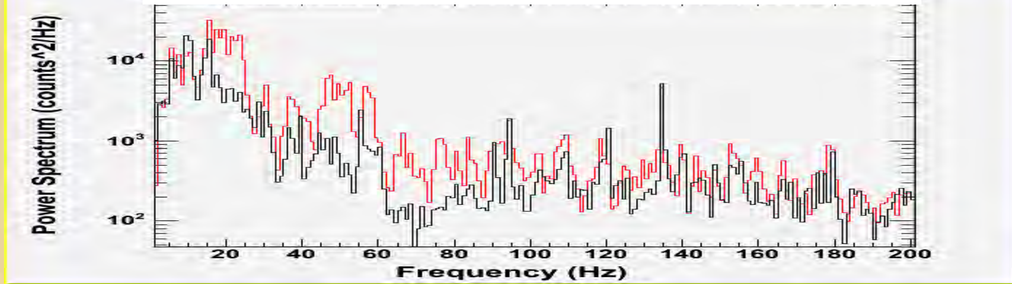


(1) the frequency spectrum of available vibrations instead of being sharply peaked at some frequency is usually very broad.

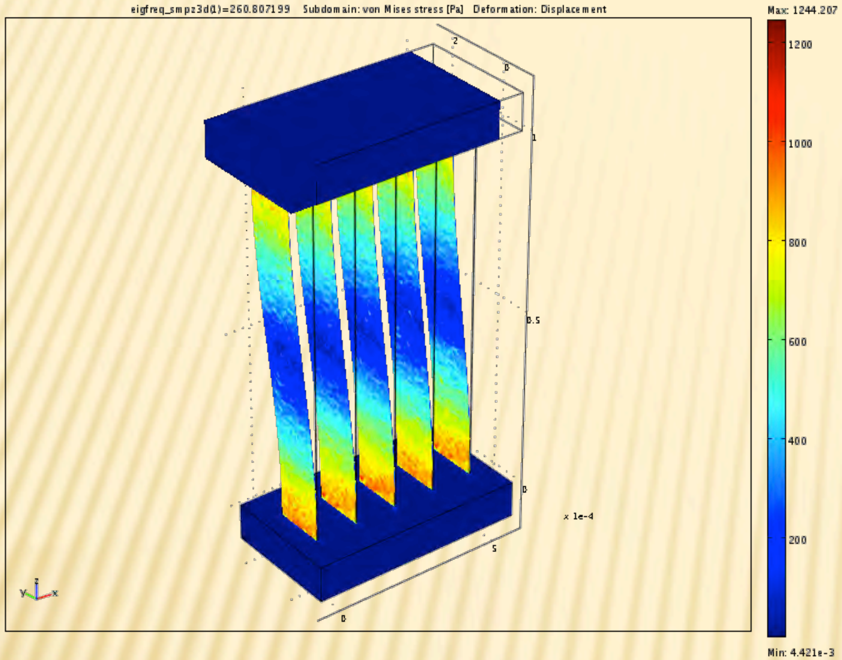
(2) The frequency spectrum of available vibrations is particularly rich in energy in the low frequency part… and it is very difficult, if not impossible, to build small low-frequency resonant systems…



Acoustic noise – quiete working env.

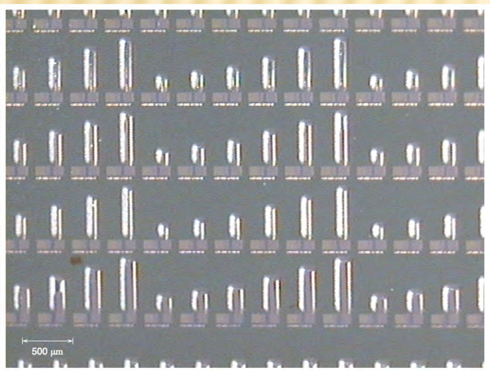


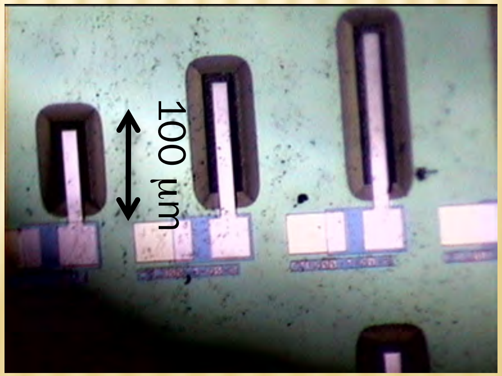
Micro energy harvesting system…

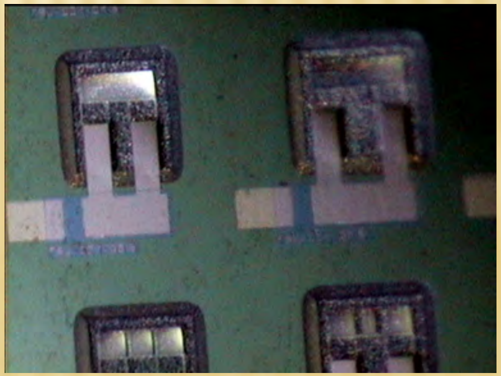


25 μm thick
1 mm high

Freq. 10 KHz







Collaboration with CEA-LETI Grenoble (FR)

VIBRATIONS ENERGY HARVESTING

Whish list for the perfect vibration harvester

1) Capable of harvesting energy on a broad-band
2) No need for frequency tuning
3) Capable of harvesting energy at low frequency

1) Non-resonant system
2) “Transfer function” with wide frequency resp.
3) Low frequency operated

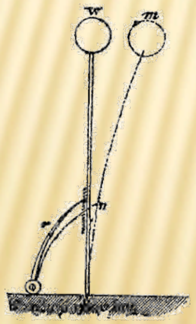
NOISE ENERGY HARVESTING

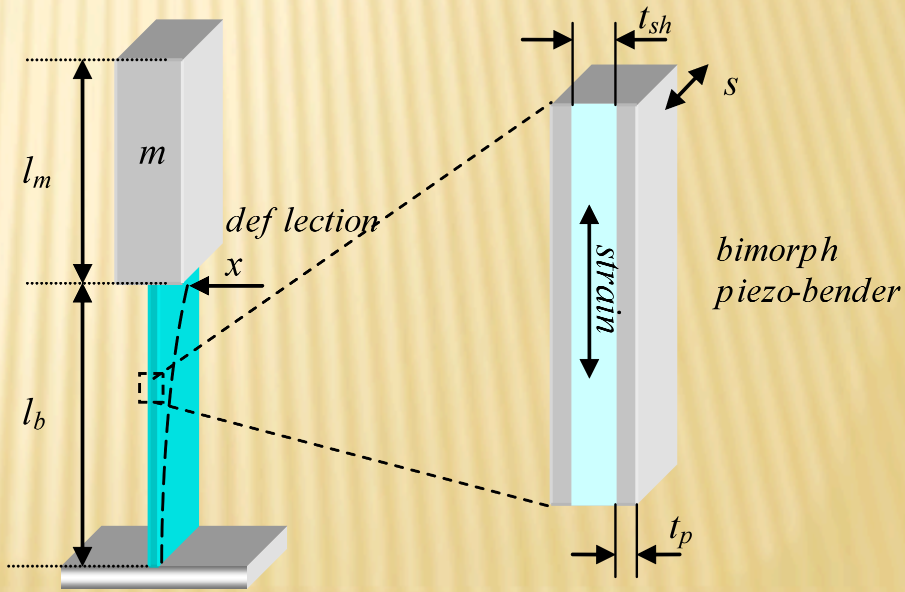
NON-Linear mechanical oscillators

1) Non-resonant system
2) “Transfer function” with wide frequency resp.
3) Low frequency operated

Example…

Inverted pendulum



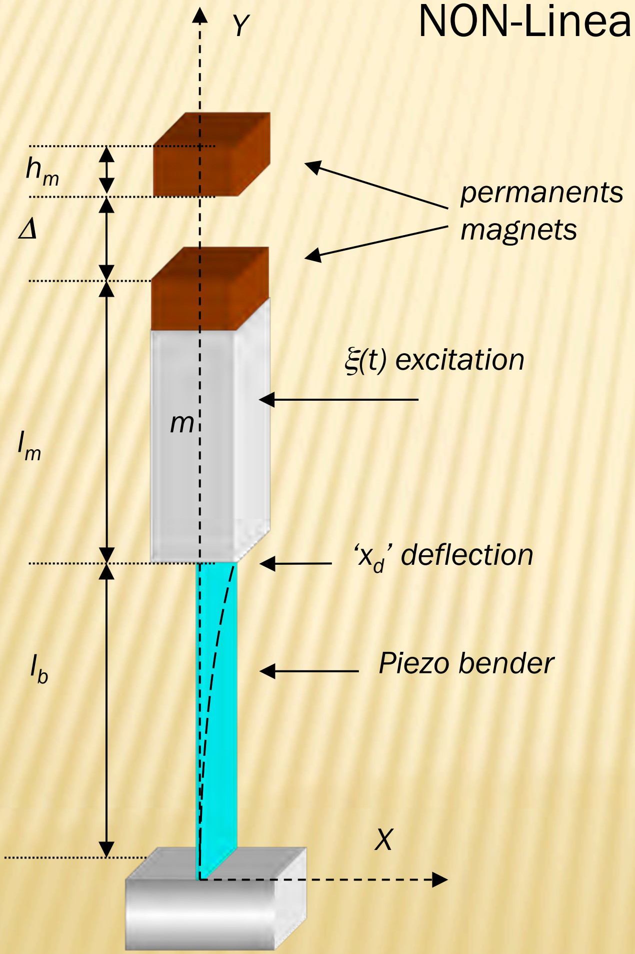


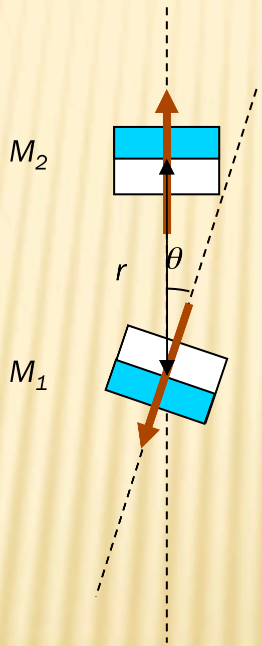
F. Cottone, PhD Thesys, Perugia 2007

NOISE ENERGY HARVESTING

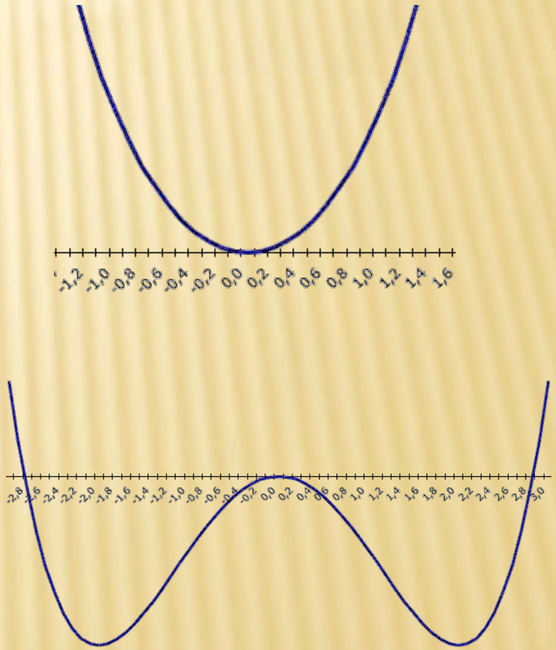
NON-Linear mechanical oscillators

NON-Linear Inverted pendulum



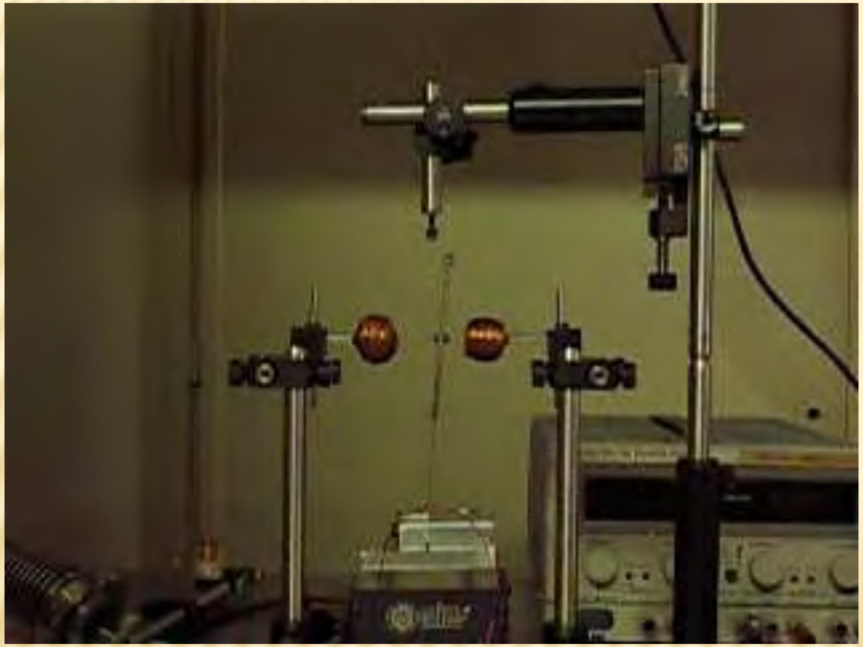


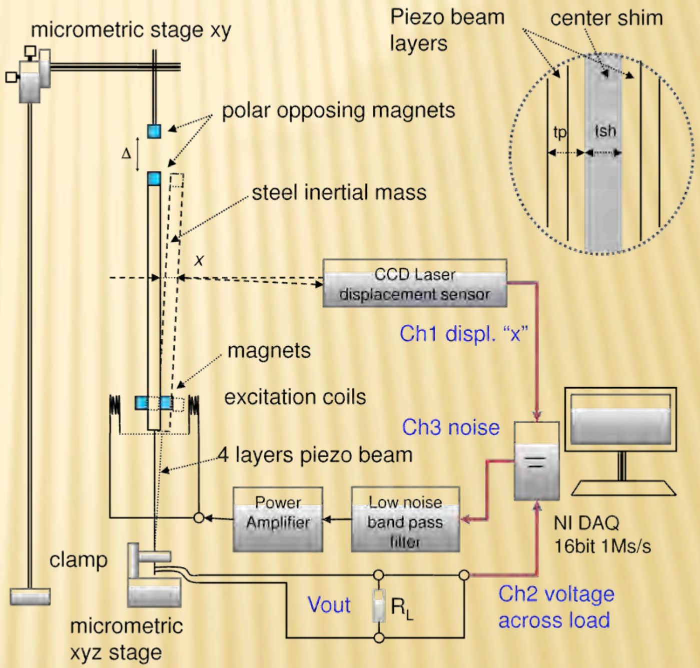
b)



NOISE ENERGY HARVESTING

NON-Linear mechanical oscillators



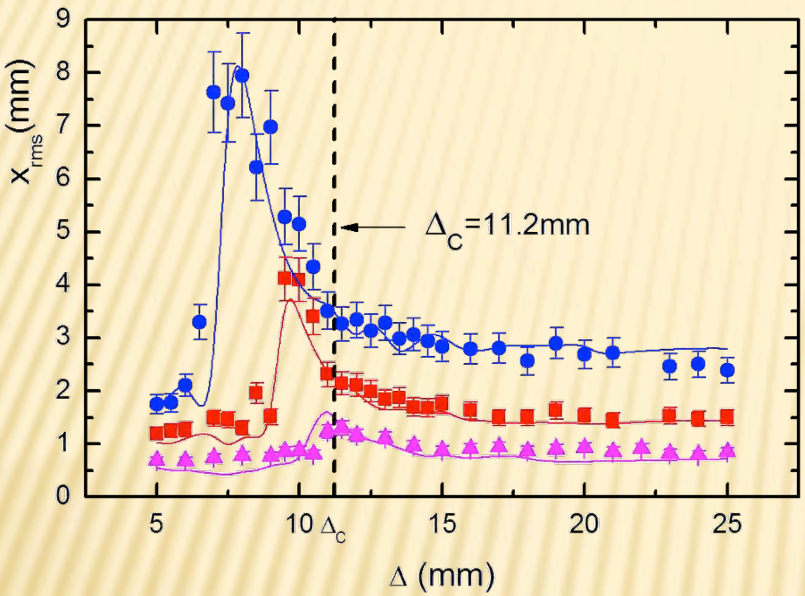


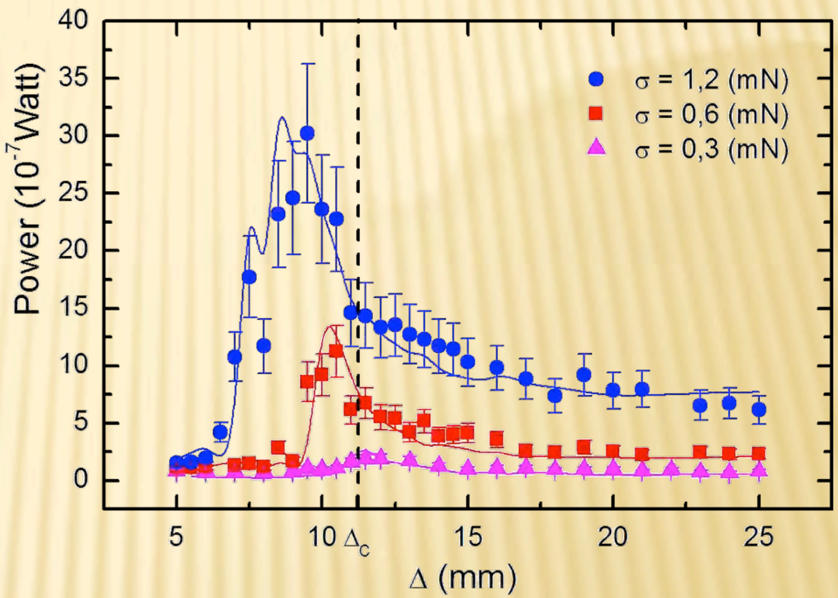
http://www.nipslab.org/node/1676

Nonlinear Energy Harvesting, F. Cottone; H. Vocca; L. Gammaitoni **Phys. Rev. Lett.**, 102, 080601 (2009)

NOISES ENERGY HARVESTING

NON-Linear mechanical oscillators

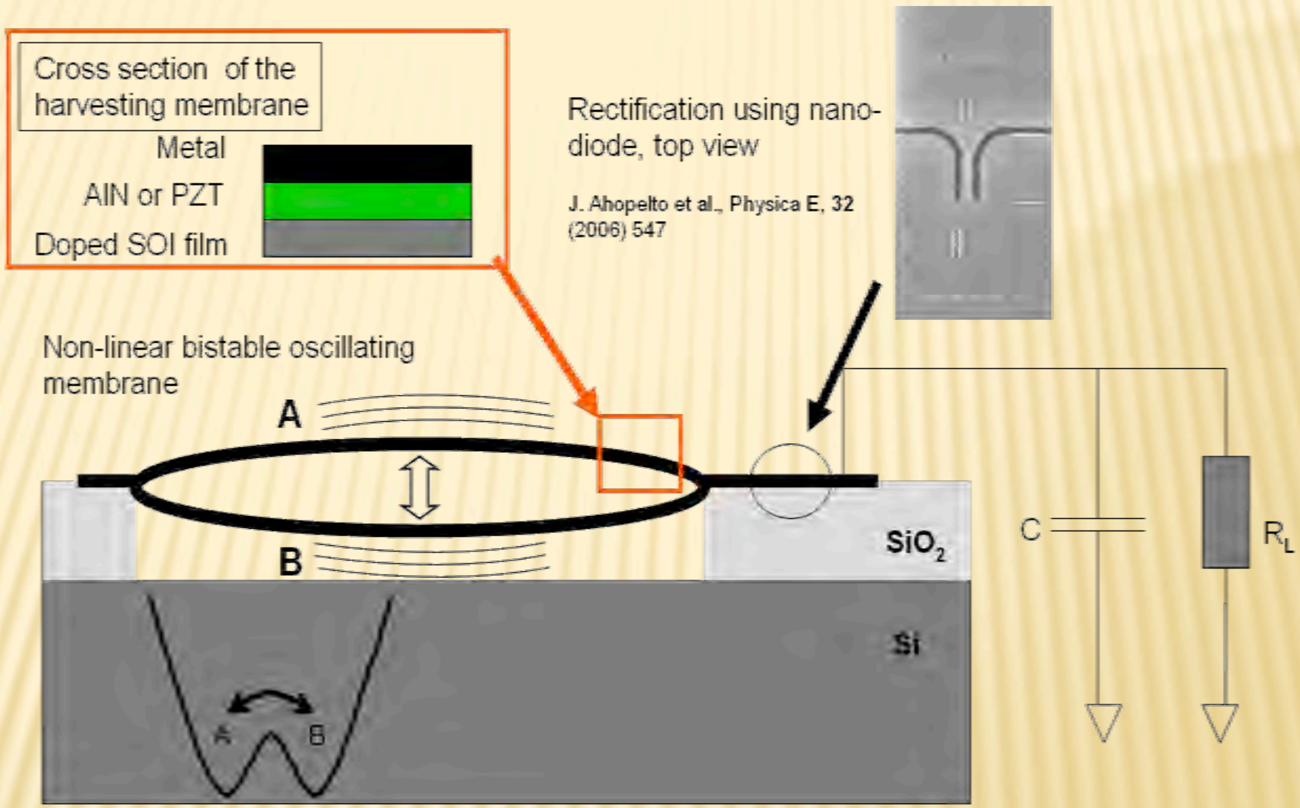




Nonlinear Energy Harvesting, F. Cottone; H. Vocca; L. Gammaitoni **Phys. Rev. Lett.**, 102, 080601 (2009)

NANOPOWER

Nanomechanical nonlinear oscillators



Sketch of a multi-stable oscillator based on clamped membranes. The kinetic energy of the nonlinear vibration is converted into electric energy by either AlN or PZT membrane sandwiched between the electrodes. The voltage is then rectified by a nanodiode integrated to the SOI film

ICT RELATED INITIATIVES FUNDED BY EC (COORDINATED BY NIPS LAB)

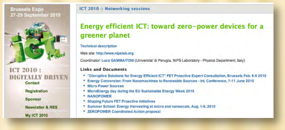
NANOPOWER

6 partners: Wurzburg (Ger), ICN (Sp), VTT (Fi), Univ Geneva (Ch), Unicam (It)
2.6 M€, 3 years, lead by NiPS
www.nanopwr.eu

ZEROPOWER

4 partners: UAC (Sp), Tyndal (Ir), Univ Glasgow (UK)
0.6 M€, 3 years, lead by NiPS

Networking session at ICT2010



Scientific session at FET11

Dissemination activity

Scientific Sessions

"Energy efficient ICT: toward zero-power devices for a greener planet"

A networking session has been organized at the ICT2010 conference, 28th September 2010 in Brussels

NANOENERGY LETTERS

NANOENERGY LETTERS is a newsletter created in order to help the circulation of news and thoughts about micro and nano energies. But... what are micro and nano energies? With these terms we intend to address the many different tiny energies present in micro and nanoscale physical systems. The role of micro-energies, indeed is more and more frequently evoked in fields as diverse as nano-electronics, computer science, micro-robotics, wireless telecommunications and it is believed that in general they could play a role in powering the future generations of Information and Communication Technology (ICT) devices. In this newsletter we would like to discuss about these energies, about their role and potential applications together with the physical foundation of this discipline. This newsletter is open to the contribution of all the interested readers and is specially aimed at reaching those readers involved in industry and innovative SMEs as an humble attempt to bridge the gap between Academia and Industry. With your help we will try to keep it twice a year.

Newsletter

A digital newsletter specifically oriented for people interested in nanoscale energy harvesting technology

www.nanopwr.eu

Events

Micro Energy Day: a public awarness event

www.microenergyday.eu

Educational activity: Summer school www.nipslab.org/summerschool

2010

2011

Summer School "Energy Harvesting at micro and nanoscale"

Workshop "Energy management at micro and nanoscale"

Perugia (IT), Aug. 1-6, 2011

NANOPOWER ZEROPOWER WISEPOWER

Video available on: http://youtu.be/GrKDnEhK130

SEVENTH FRAMEWORK PROGRAMME