Noise harvesting with nonlinear oscillators

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www.nipslab.org

N.i.P.S Laboratory

Noise in Physical Systems

WISEPOWER

Contents

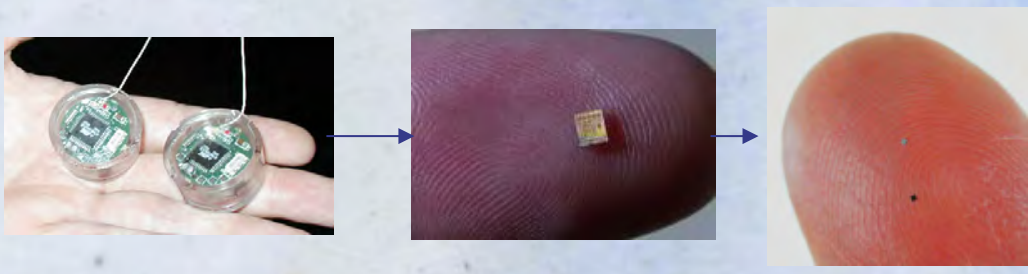
For more info see: www.nipslab.org, www.wisepower.it

Motivation: future ICT

There is an increasing demand of portable power

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



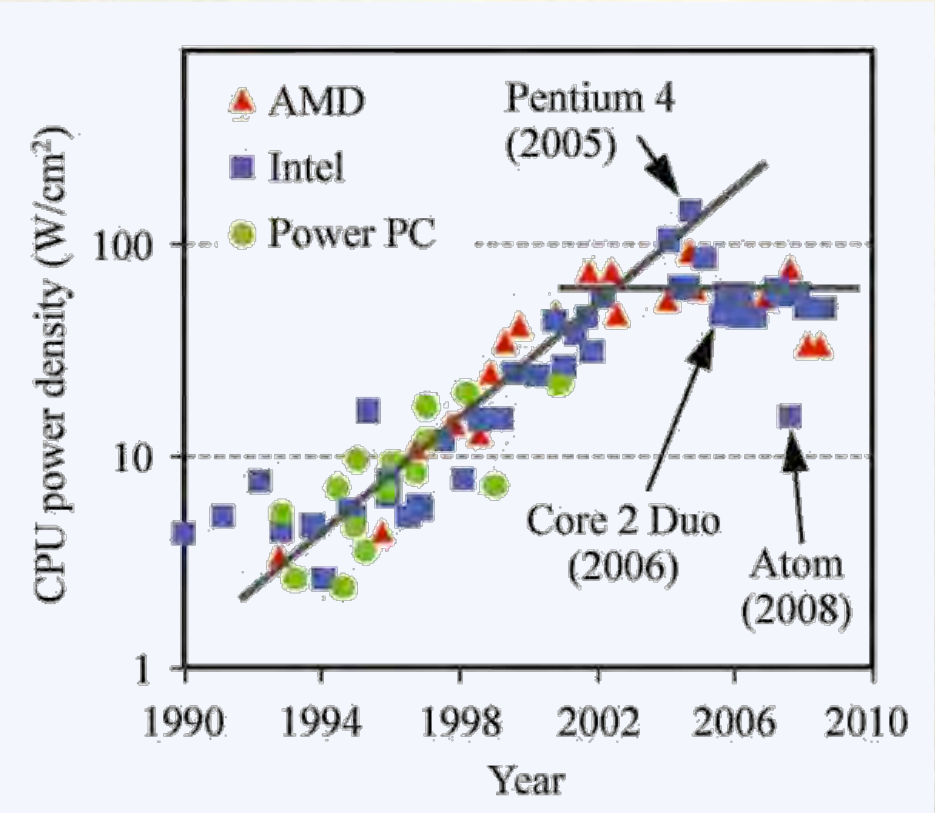
Present
(cubic centimeter)

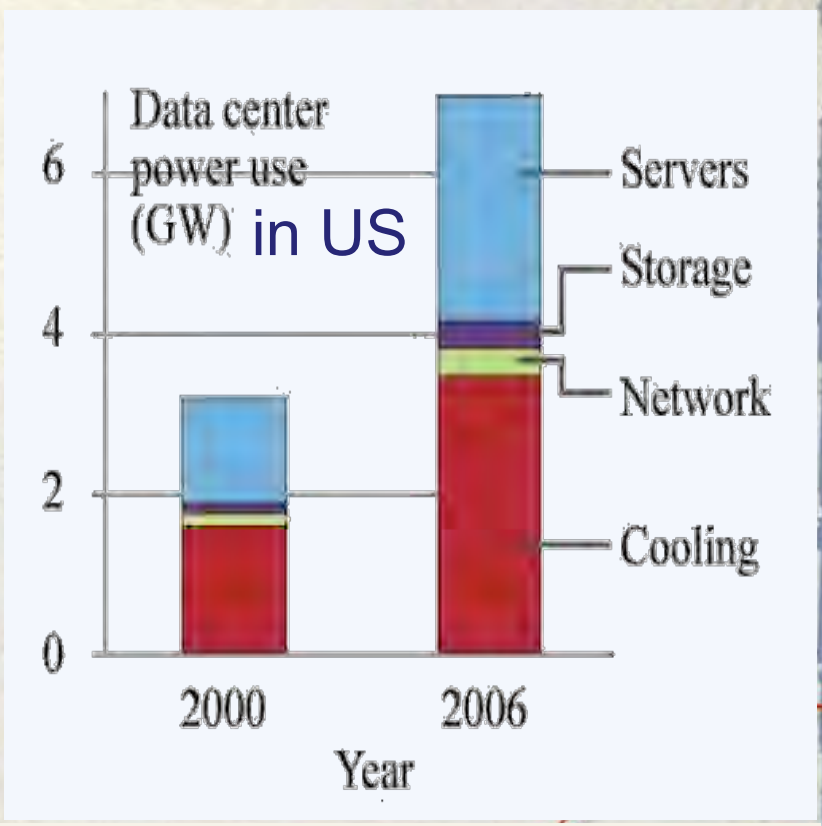
Future
(cubic sub-millimeter
sub-micrometer)

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.

ICT, dissipation, fluctuation

Quite recently ICT (Information and Communication technology) has become an interesting playground for fluctuations due to the presence of significant **dissipation**…

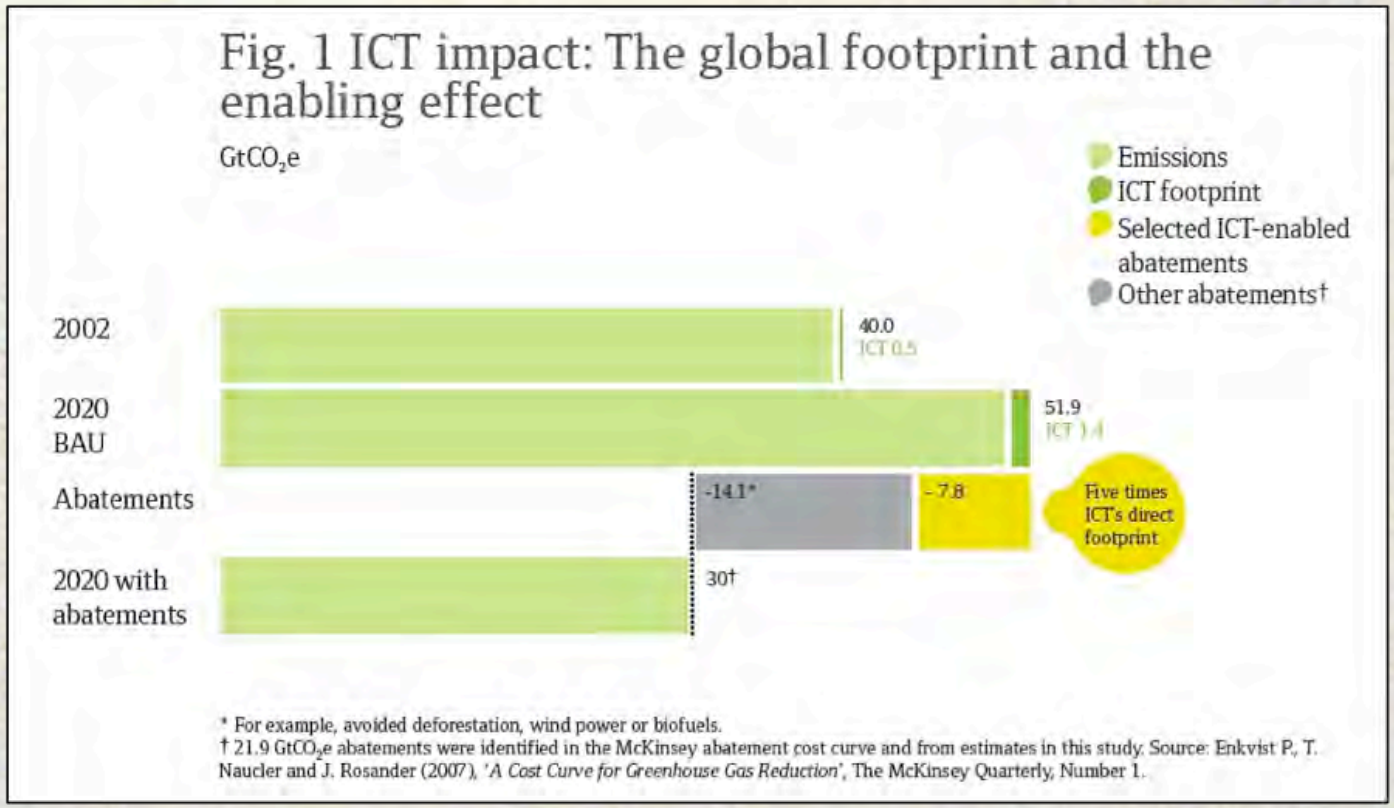




E. Pop, *Energy Dissipation and Transport in Nanoscale Devices*, Nano Res (2010) 3: 147–169

ICT, dissipation, fluctuation

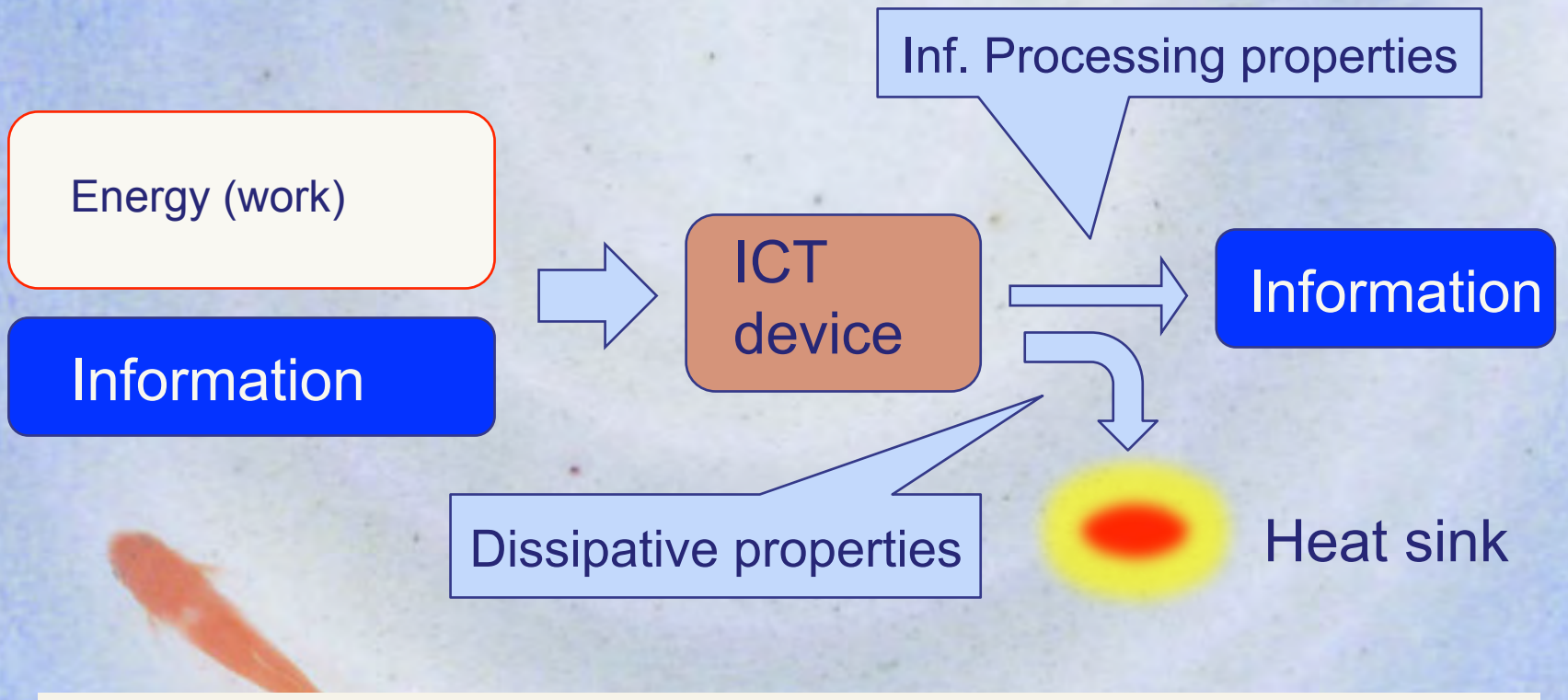
The ICT share of energy consumption has a direct inpact on our carbon footprint



Report “SMART 2020: Enabling the low carbon economy in the information age”
Climate Group of Global eSustainability Initiative (GeSI).

Let's give a closer look

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

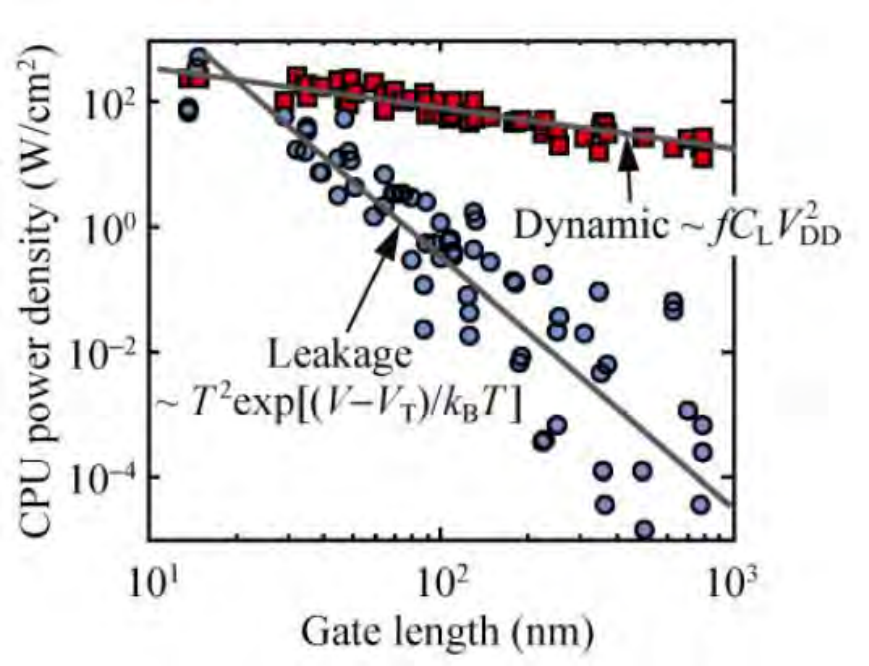
The energy efficiency issue: some clues…

Three components have been identified for digital power consumption:

- dynamic power used during switching (for charging and discharging the inverter load)
- subthreshold leakage power
- short-circuit power

However the present modelling of energy dissipation mechanism is based on microscale 3D system templates and is NOT adequate to represent nanoscale 2D, 1D devices…

Knowledge needed



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

The energy efficiency issue: some more clues…

There are fundamental physics **LIMITS** that are relevant

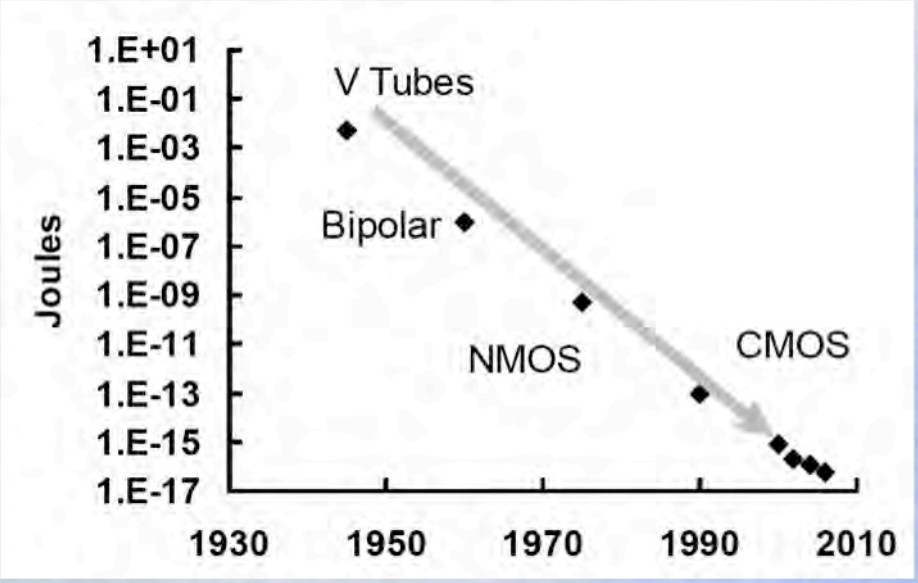
1. Landauer limit to minimum energy for logically irreversible operation

$$E_{min} = KT \log 2 = 10^{-21} \text{ J}$$

2. Quantum limit from Energy/time uncertainity relation

$$\Delta t = \pi\hbar/2E$$

Margolus, N. & Levitin, L. B.
The maximum speed of dynamical evolution.
Physica D 120, 188–195 (1998)



Energy per elementary logic operation. From: Shekhar Borkar, Electronics beyond nano-scale CMOS, Proceedings of the 43rd annual Design Automation Conference, p. 807, San Francisco, CA, USA, 2006

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

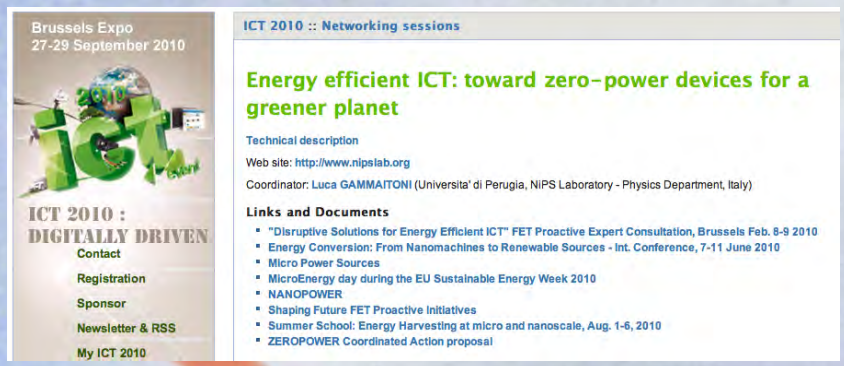
At the nanoscale, in fact, thermal fluctuations, negligible at higher scale, become the most relevant factor and non-equilibrium thermodynamics approaches are required as opposed to the traditional concepts based on equilibrium energy balances. *Non-equilibrium work relations,* mainly in the form of "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).
-Rubi, J Miguel, "Does Nature Break the Second Law of Thermodynamics?"; Scientific American, October 2008

ICT related initiatives funded by EC

Towards Zero-Power ICT – call 5, FP7-ICT-2009-5

NANOPOWER



Networking session at ICT2010

http://ec.europa.eu/information_society/events/cf/ict2010/item-display.cfm?id=3440

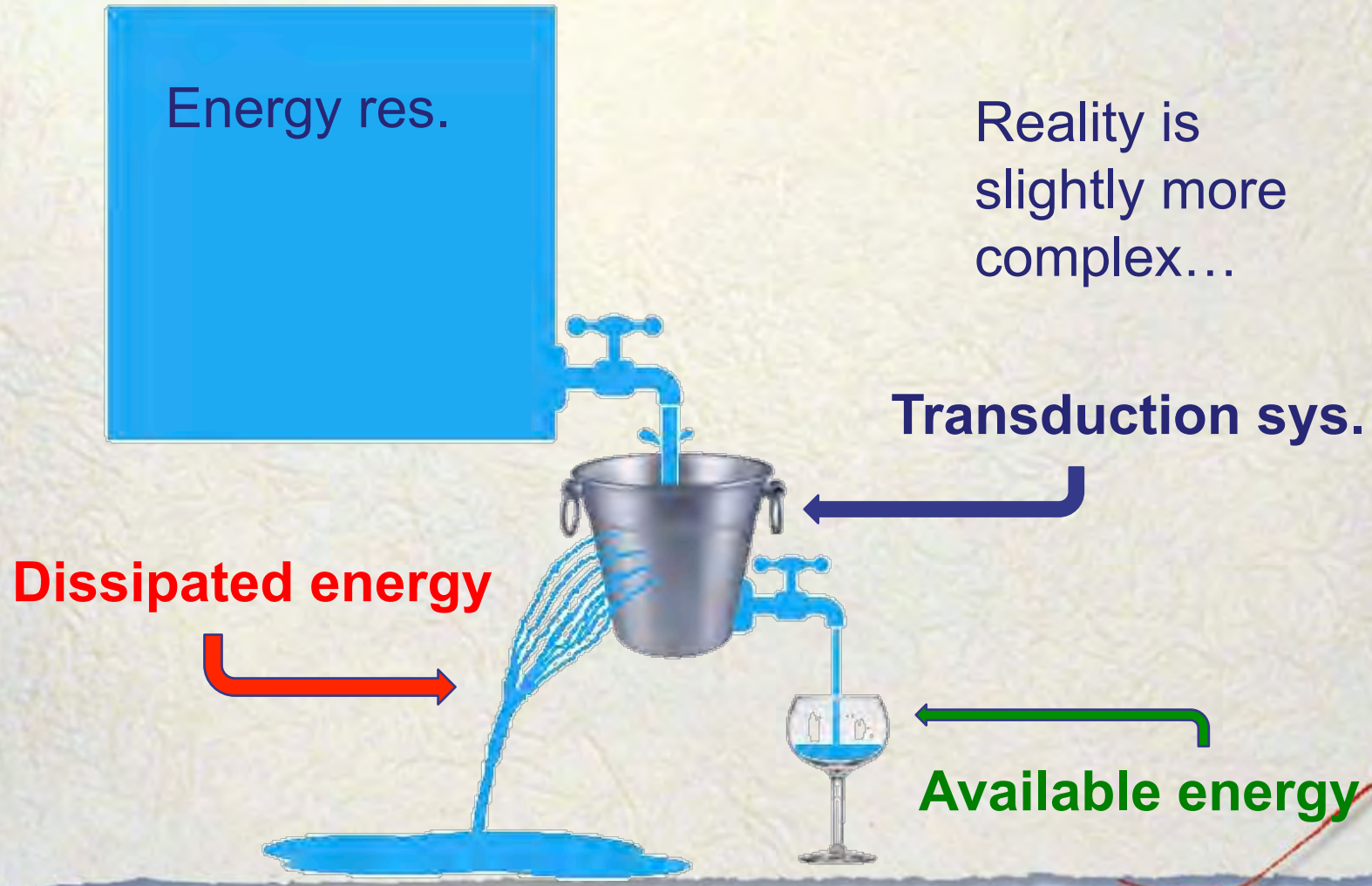
FET Flagship initiative: **"SCIENCE & POLICY FORUM on FET Flagships' Workshop Brussels, 9 - 10 June 2010**

Energy harvesting basic ideas…

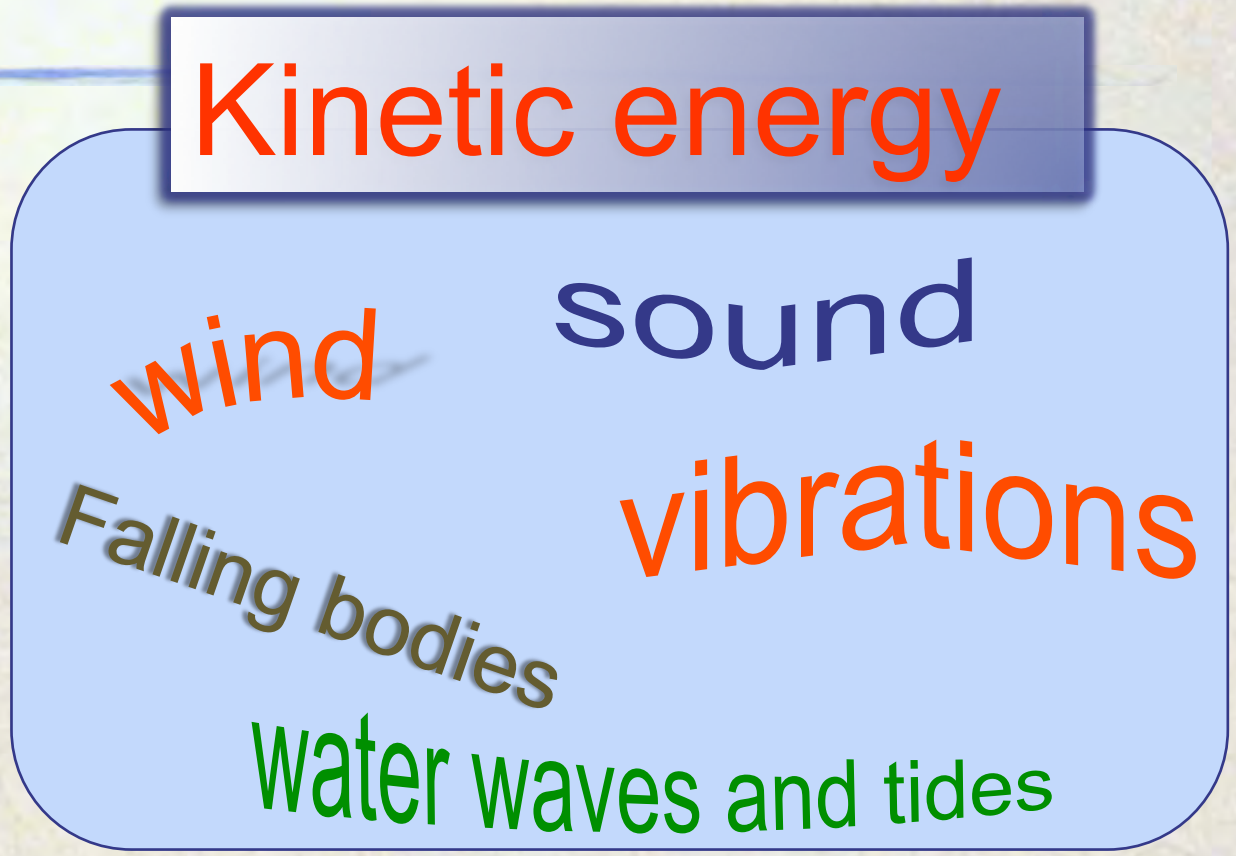
ENERGY

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

it is more like…



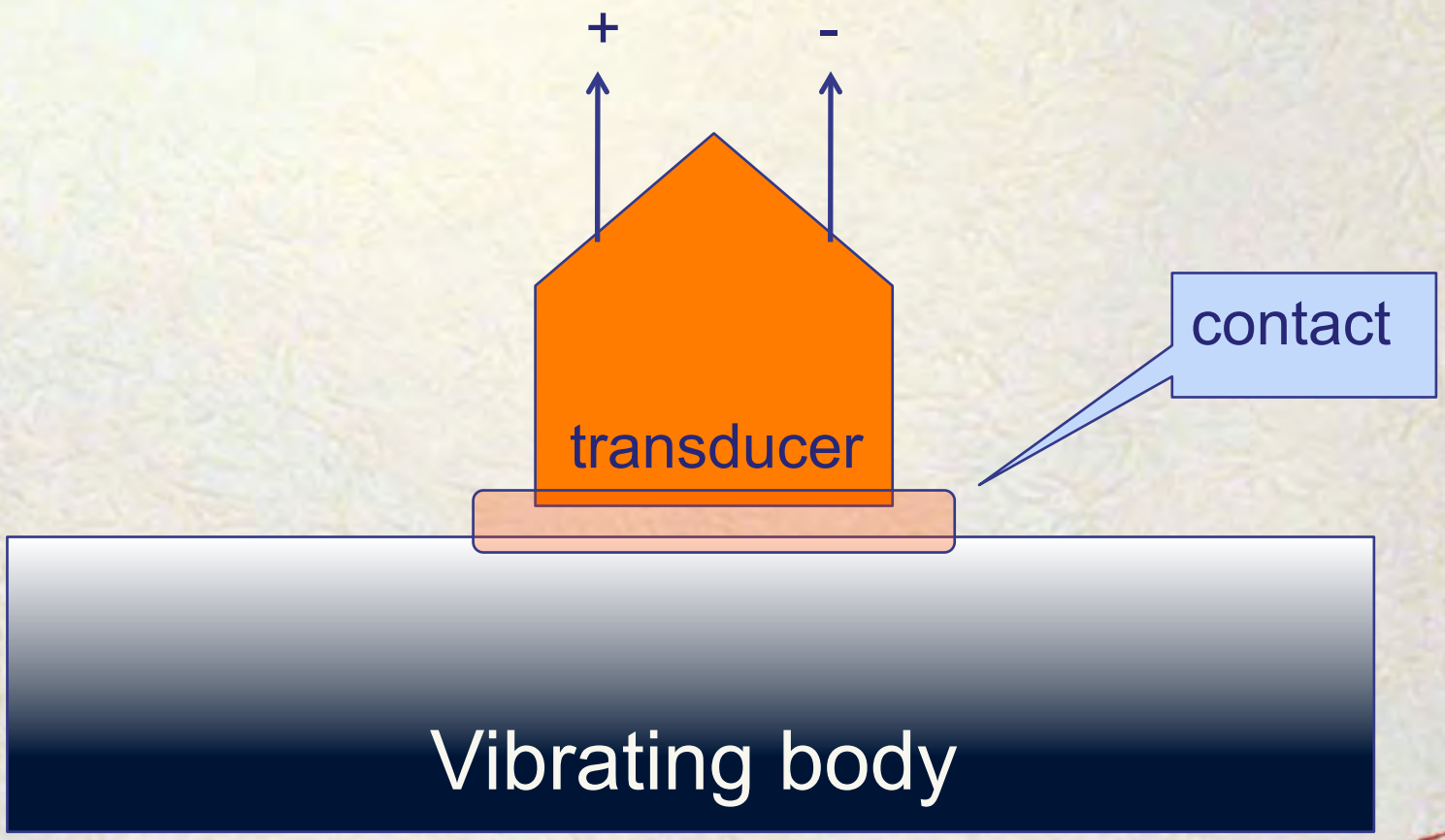
Energy harvesting basic ideas



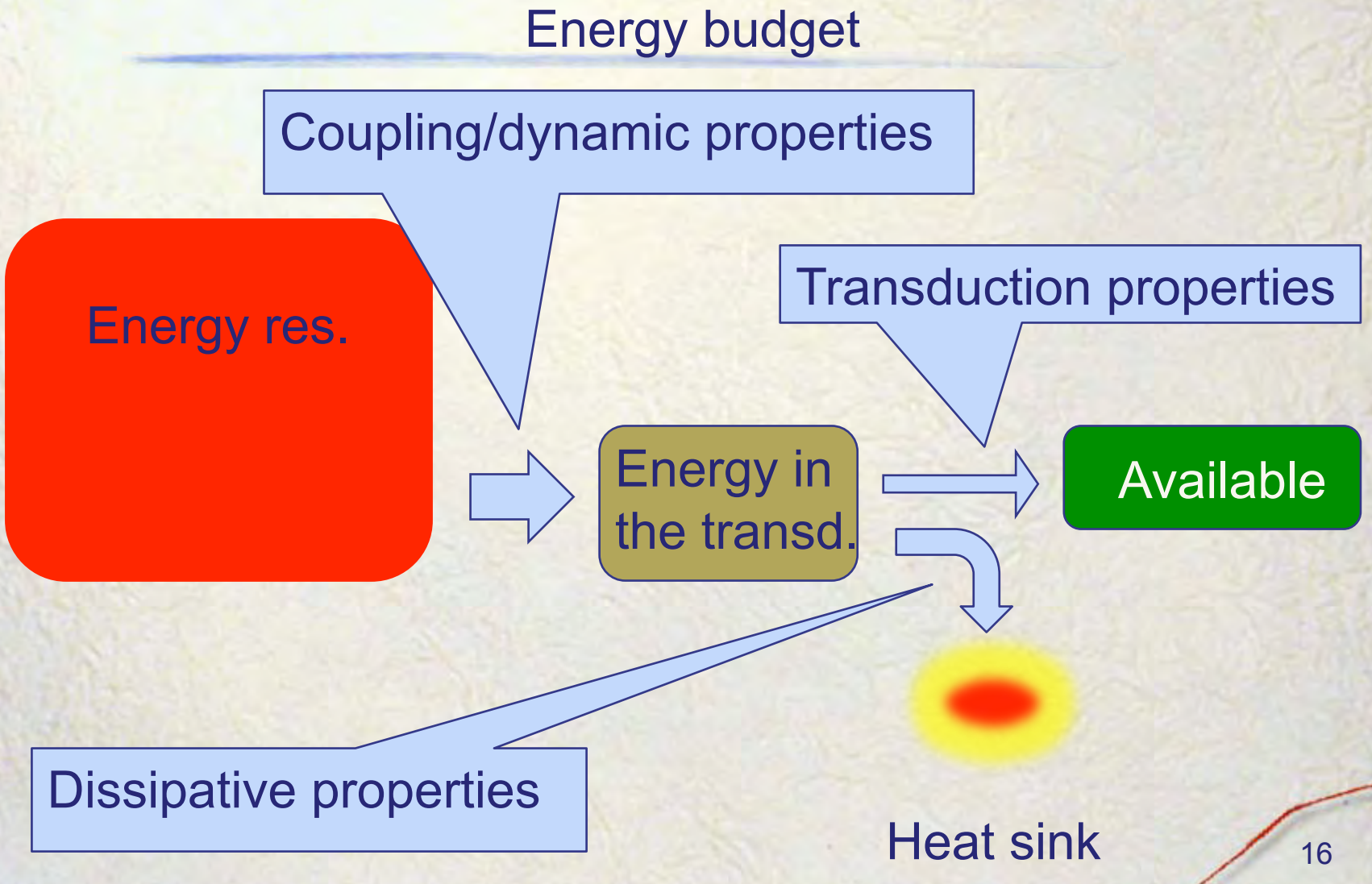
Focus on vibrations of solid bodies….

Vibrations energy harvesting

Basic Scheme

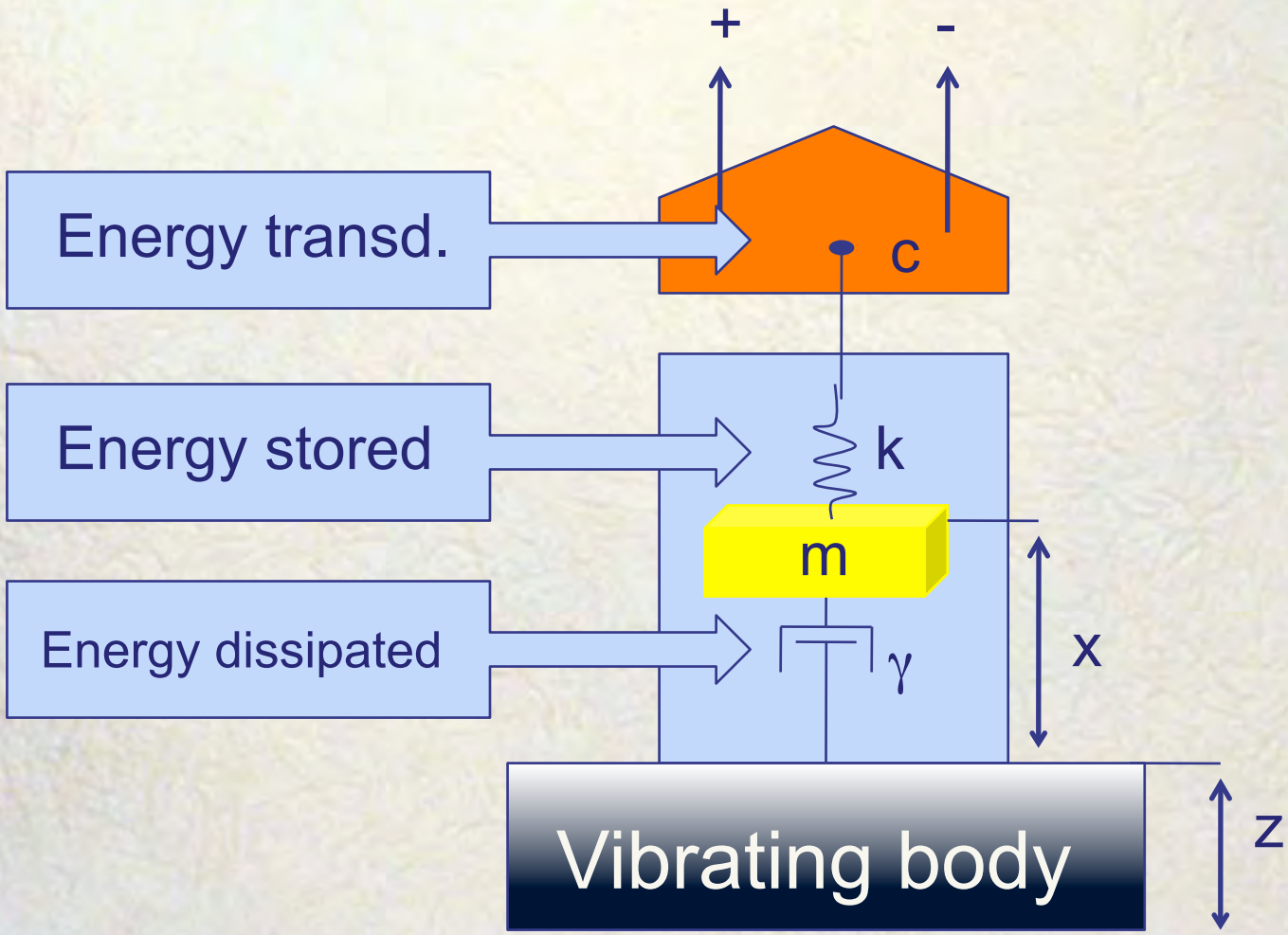


Vibrations energy harvesting

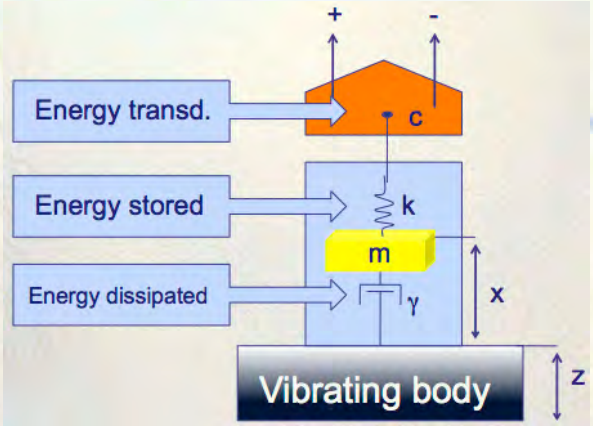


Vibrations energy harvesting

Dynamical model



Vibrations energy harvesting



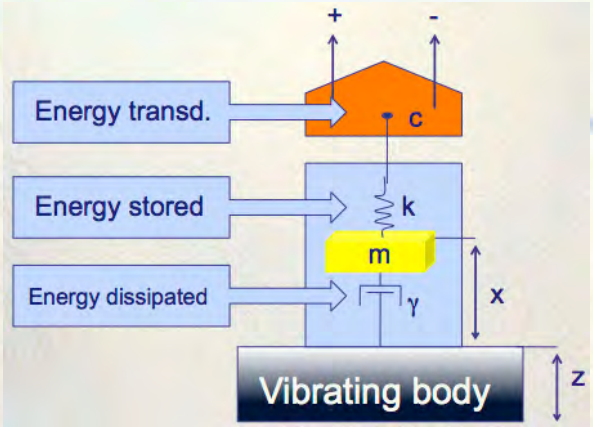
Dynamical model

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

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

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

$$\dot{V} = F(\dot{x},V)$$

Details depend on the physics…

Three main transduction mechanisms…

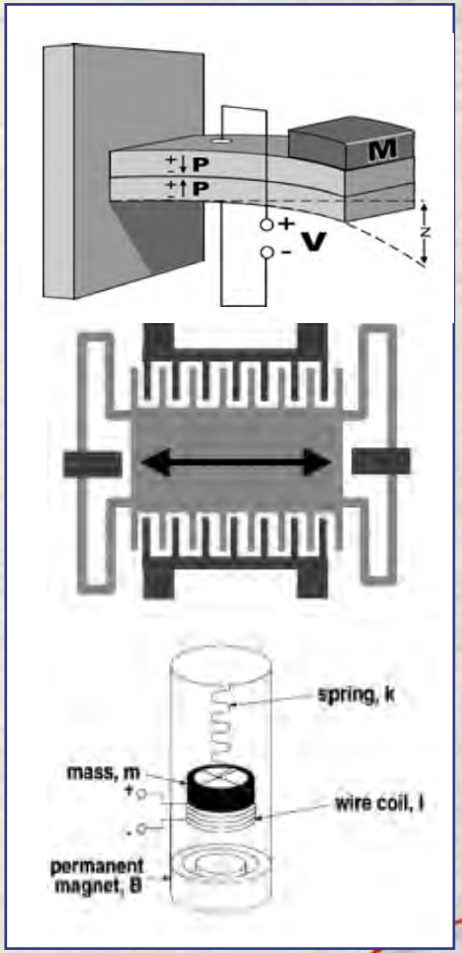
Vibrations energy harvesting

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

Transduction mechanisms: focus on Piezo

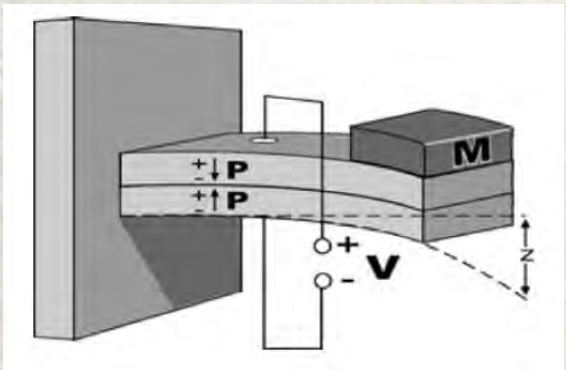
1 Piezoelectric: dynamical strain is converted into voltage difference.

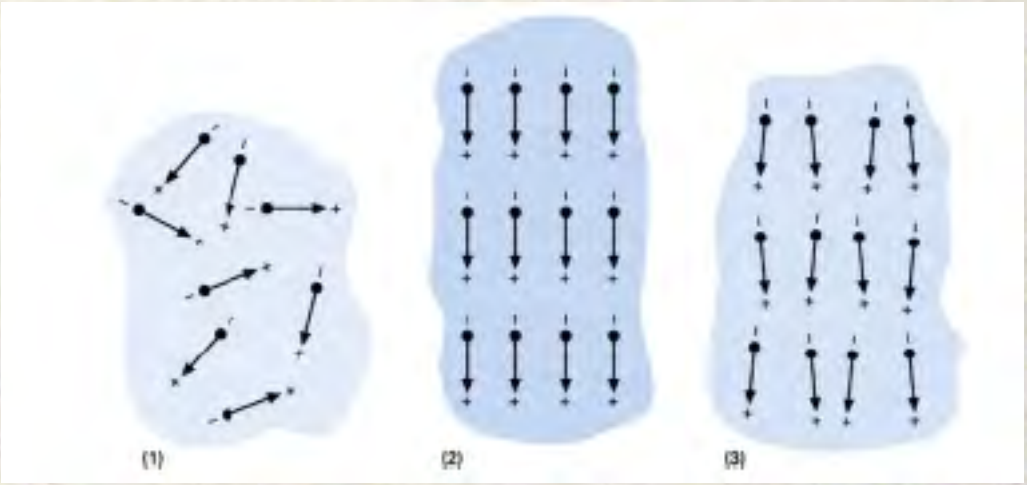
Type	Governing Equation	Practical Maximum	Theoretical Maximum
Piezoelectric	$u = \sigma_y^2 k^2 / 2Y$	17.7 mJ/cm^3	335 mJ/cm^3
Electrostatic	$u = \frac{1}{2}\varepsilon E^2$	4 mJ/cm^3	44 mJ/cm^3
Electromagnetic	$u = B^2 / 2\mu_0$	4 mJ/cm^3	400 mJ/cm^3

Vibrations energy harvesting

Transduction mechanisms

1 Piezoelectric: dynamical strain is converted into voltage difference.





Vibrations energy harvesting

Transduction mechanisms

1 Piezoelectric: dynamical strain is converted into voltage difference.

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

$$\dot{V} = K_c\dot{x} - \frac{1}{\tau_p}V$$

The Physics of piezo materials

The available power is proportional to V^2

Vibrations energy harvesting

Transduction mechanisms

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

$$\dot{V} = K_c\dot{x} - \frac{1}{\tau_p}V$$

$U(x)$ Represents the Energy stored

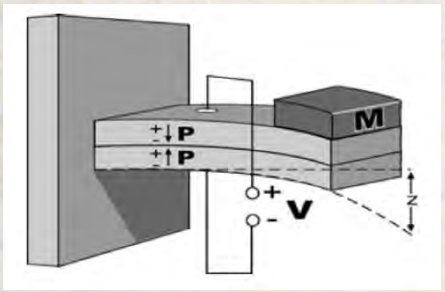
When $U(x) = \frac{1}{2}kx^2$ it is called a linear system

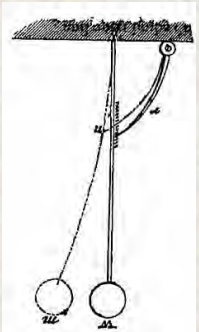
Linear systems

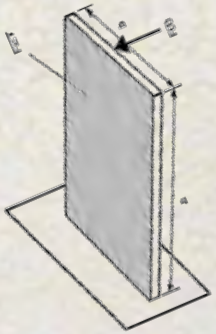
When $U(x) = \frac{1}{2} k x^2$ it is called a linear system

Linear systems have some interesting features… (and engeneers like them most)

1) There exist a simple math theory to solve the eq.s
2) They have a resonant behaviour (resonance freq.)
3) They can be “easily” realized with catilevers and pendula

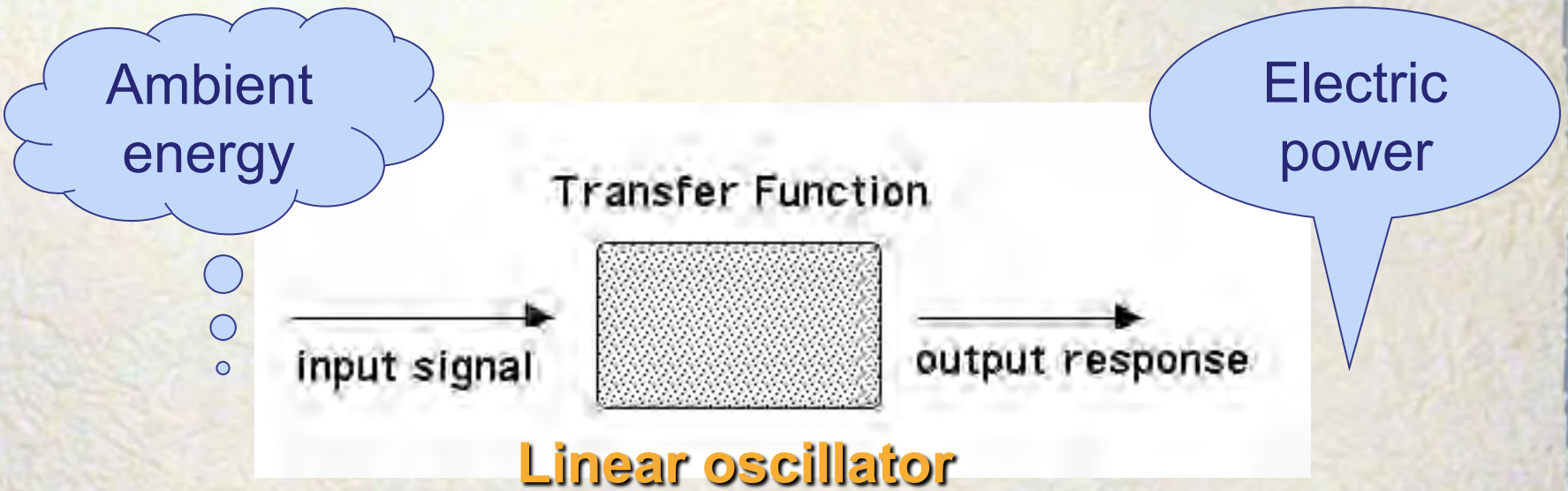






Vibrations energy harvesting

Linear systems

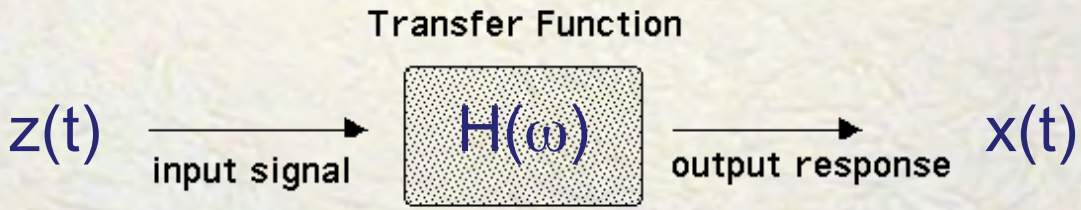


The transfer function is a math function of the frequency, in the complex domain, that can be used to represent the performance of a linear system

Vibrations energy harvesting

Linear systems

In a linear system, thanks to the transfer function H (ω), the output spectrum can be obtained from the input spectrum through a simple multiplication…



$$S_x(\omega) = |H(\omega)|^2 S_z(\omega)$$

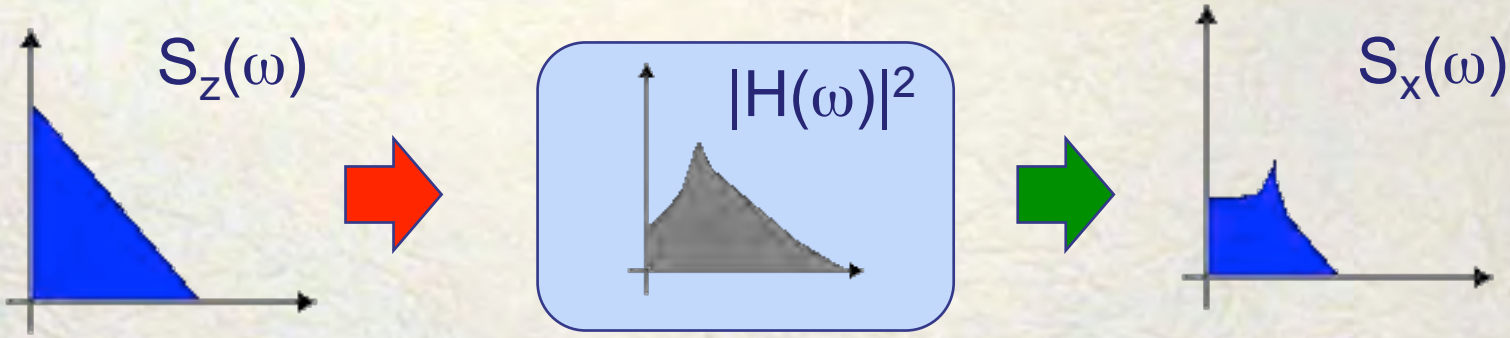
Output power spectrum

Input power spectrum

Vibrations energy harvesting

Linear systems

The transfer function is important because it acts as a filter on the incoming energy…



Freq. spectrum of the available energy

Transfer function of the transducer

Freq. spectrum of the usable energy

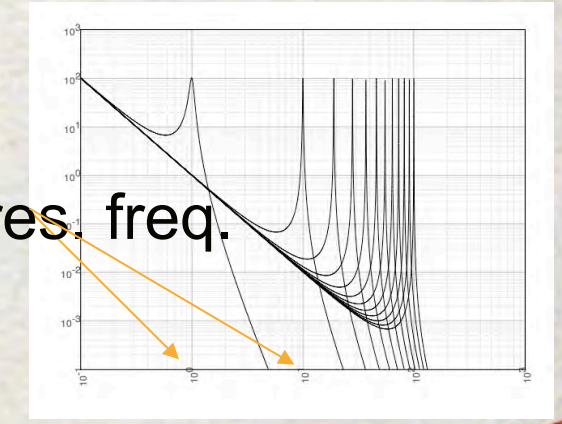
$$S_x(\omega) = |H(\omega)|^2 S_z(\omega)$$

Vibrations energy harvesting

Linear systems

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…



Why ?!!

Vibrations energy harvesting

Linear systems

For two main reasons…

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

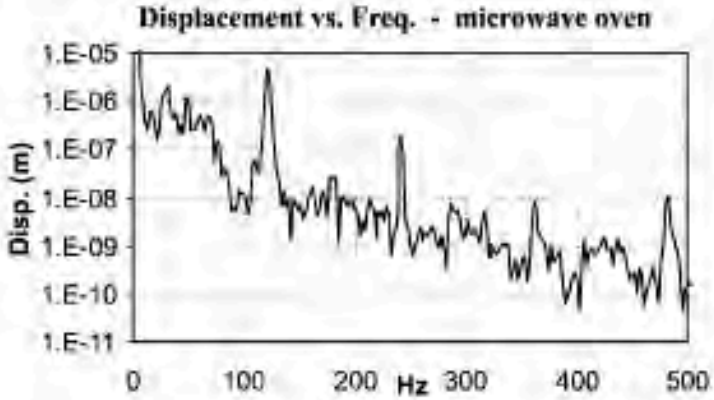
(2) The frequency spectrum of available vibrations is particularly rich in energy in the low frequency part… and it is very difficult, if not impossible, to build small low-frequency resonant systems…

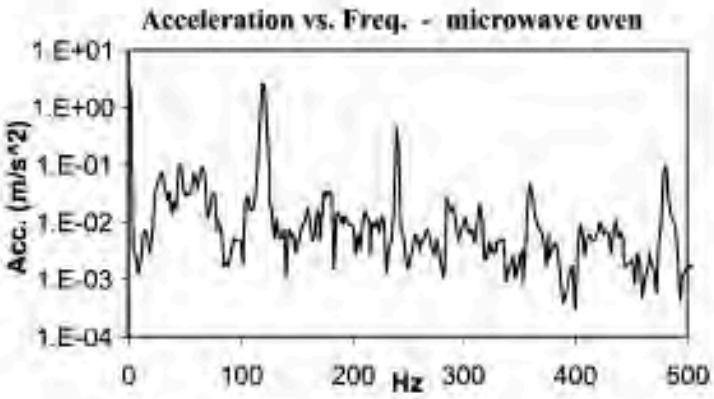
Let's see some examples…

Vibrations energy harvesting

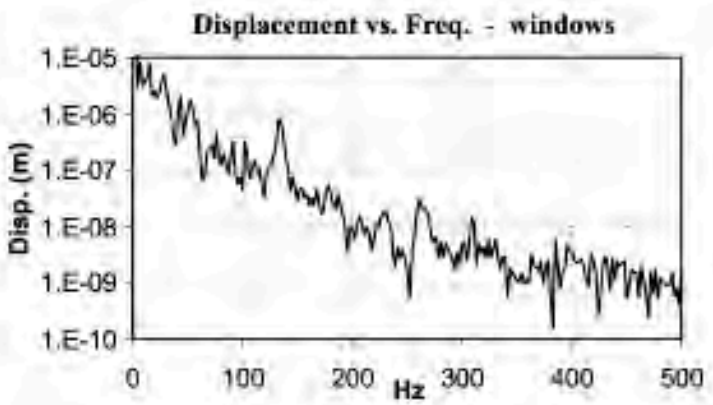
S. Roundy et al. / Computer Communications 26 (2003) 1131–1144

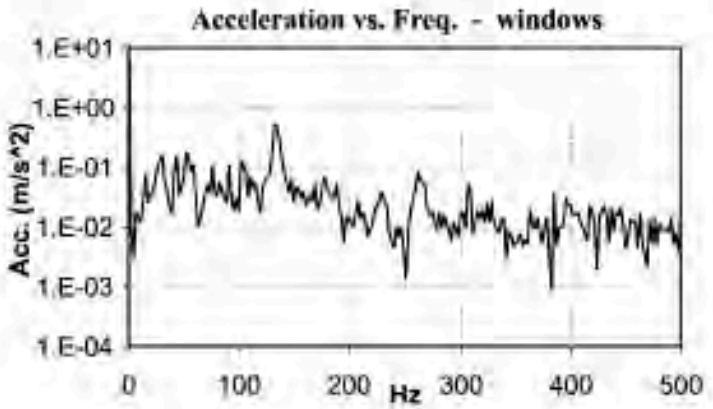
Microwave Casing





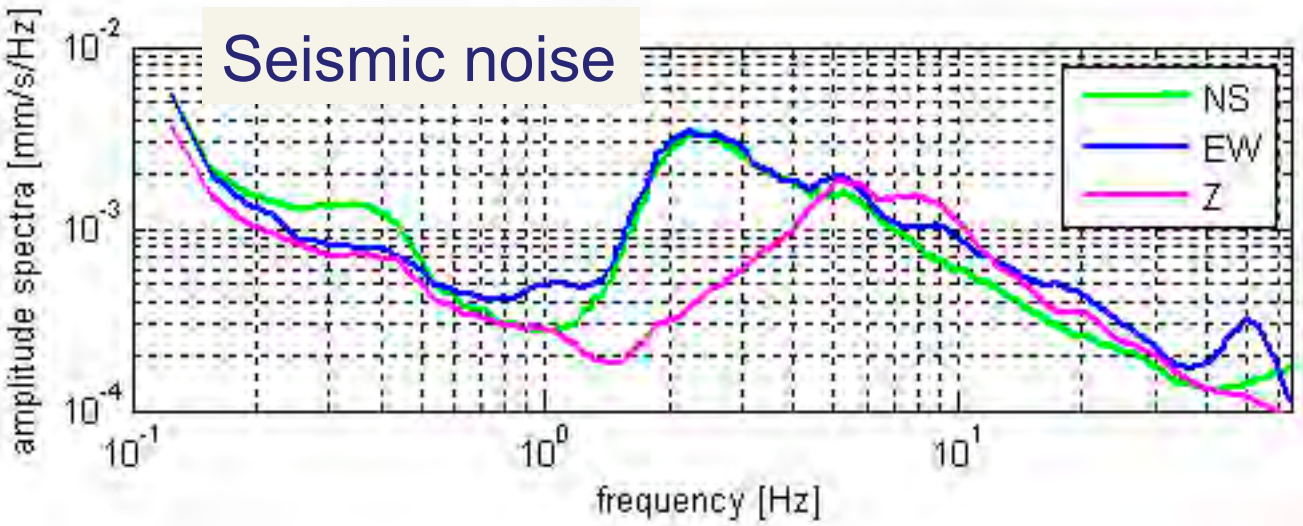
Windows Next to a Busy Street



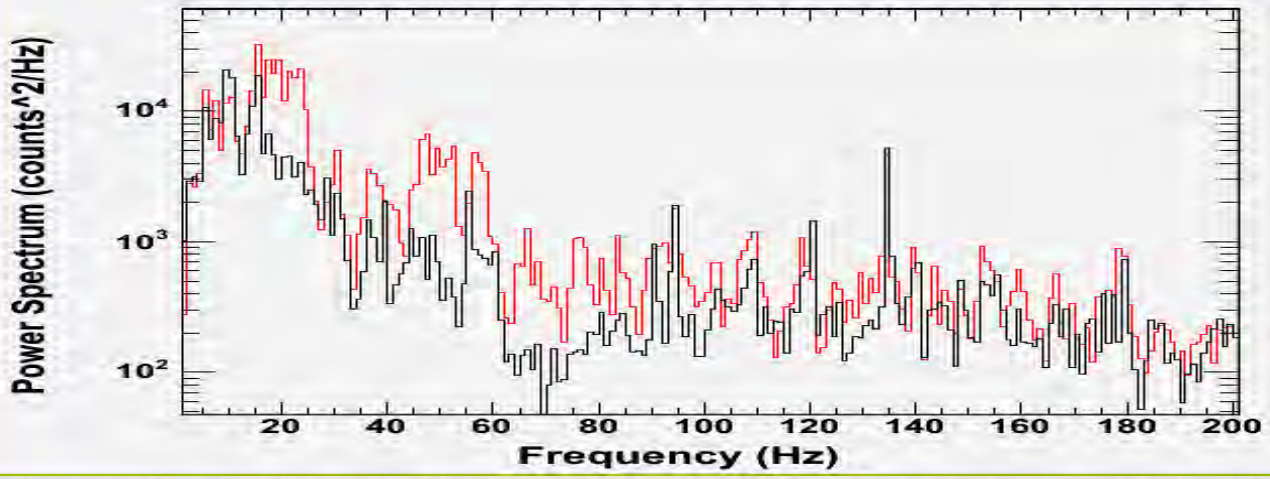


Vibrations energy harvesting

Seismic noise

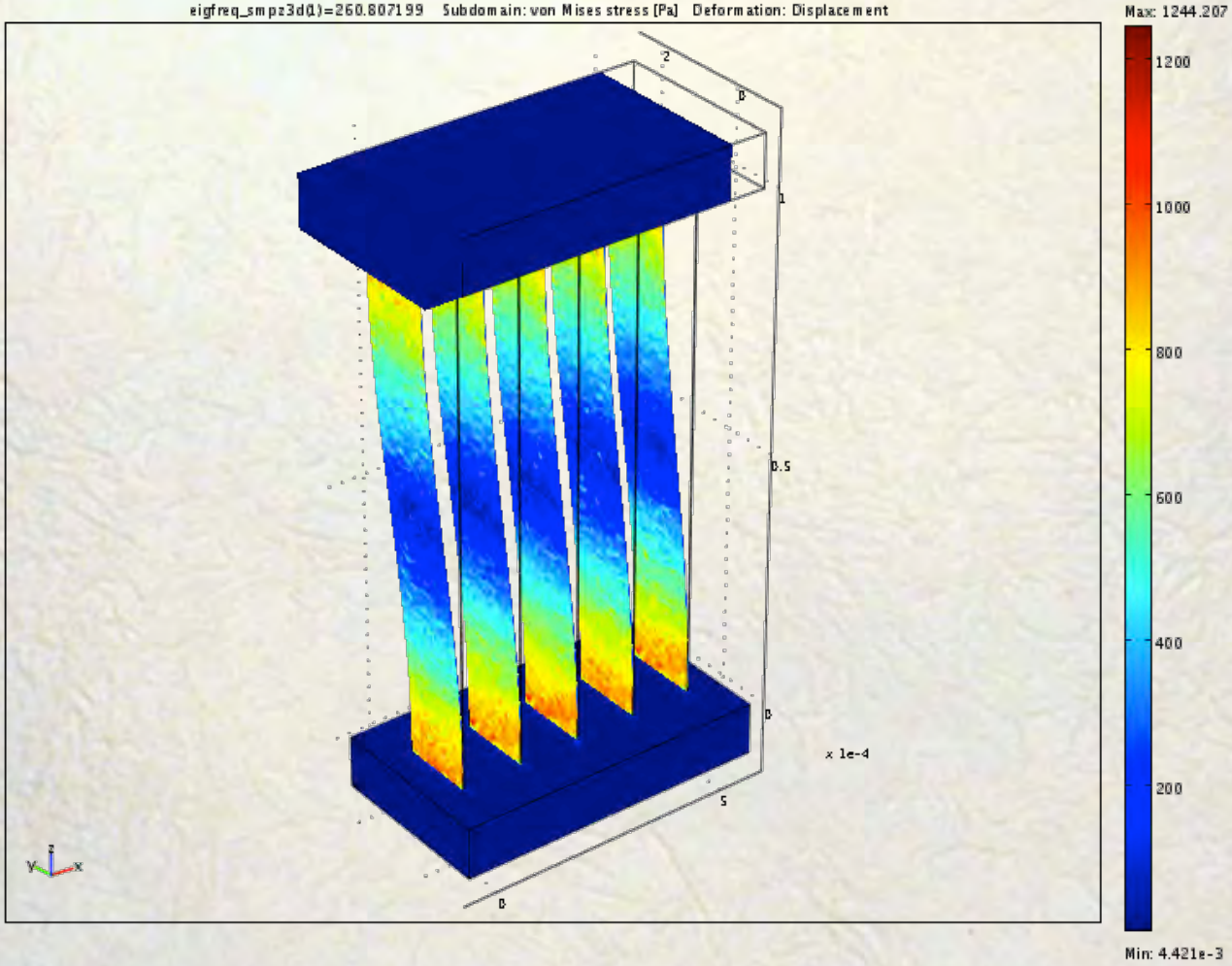


Acoustic noise – quiete working env.



Vibrations energy harvesting

Micro energy harvesting system…



25 μm thick
1 mm high

Freq. 10 KHz

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

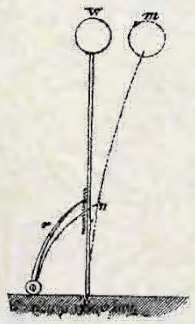
Non-linear systems

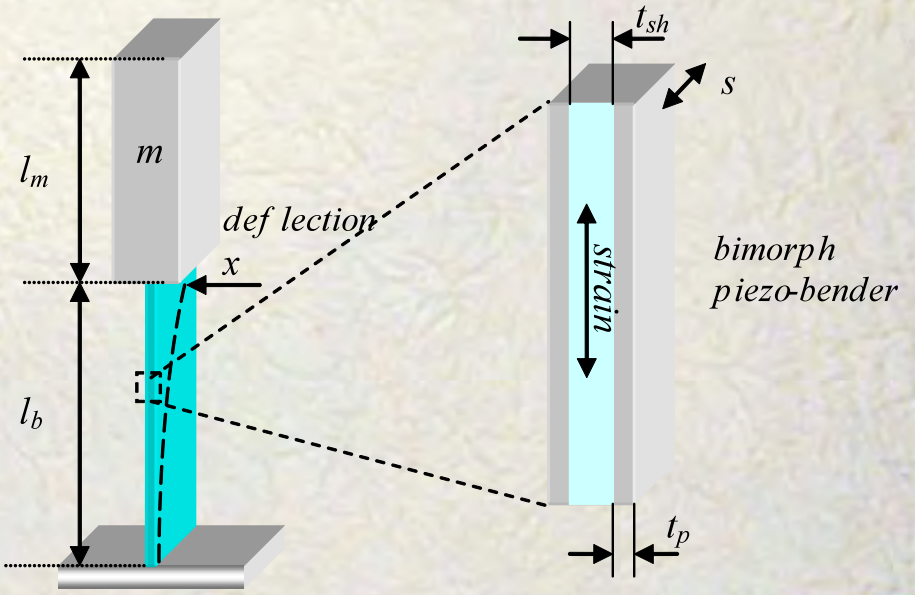
NON-Linear mechanical oscillators

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

Example…

Inverted pendulum



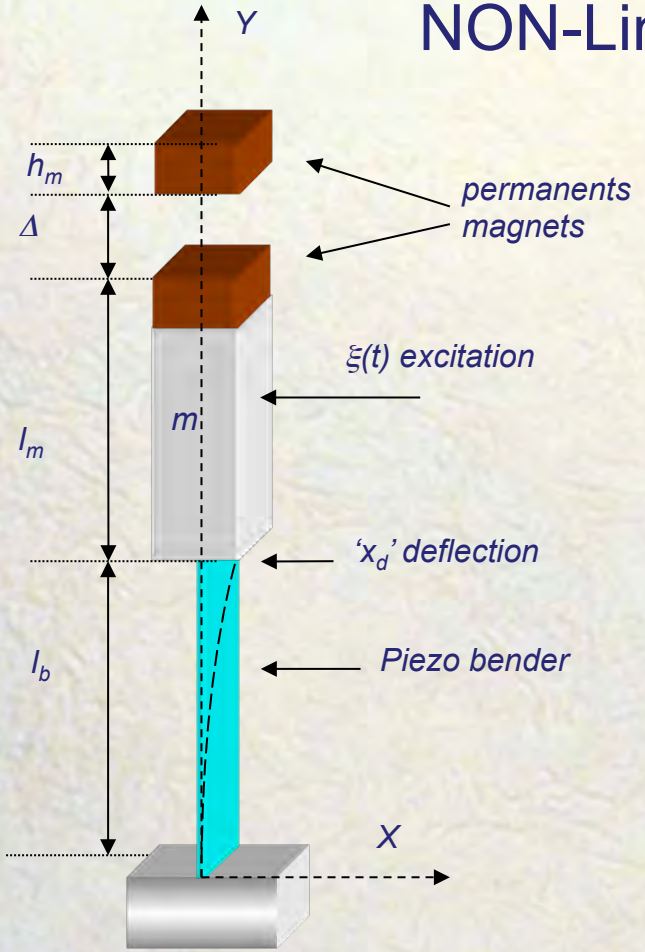


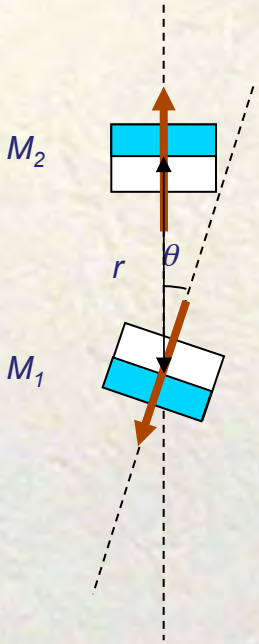
F. Cottone, PhD Thesys, Perugia 2007

Vibrations energy harvesting

NON-Linear mechanical oscillators

NON-Linear Inverted pendulum





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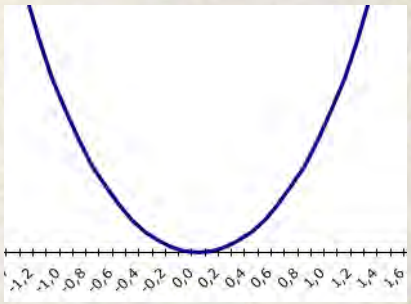
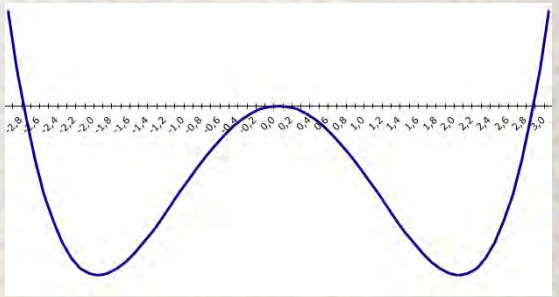
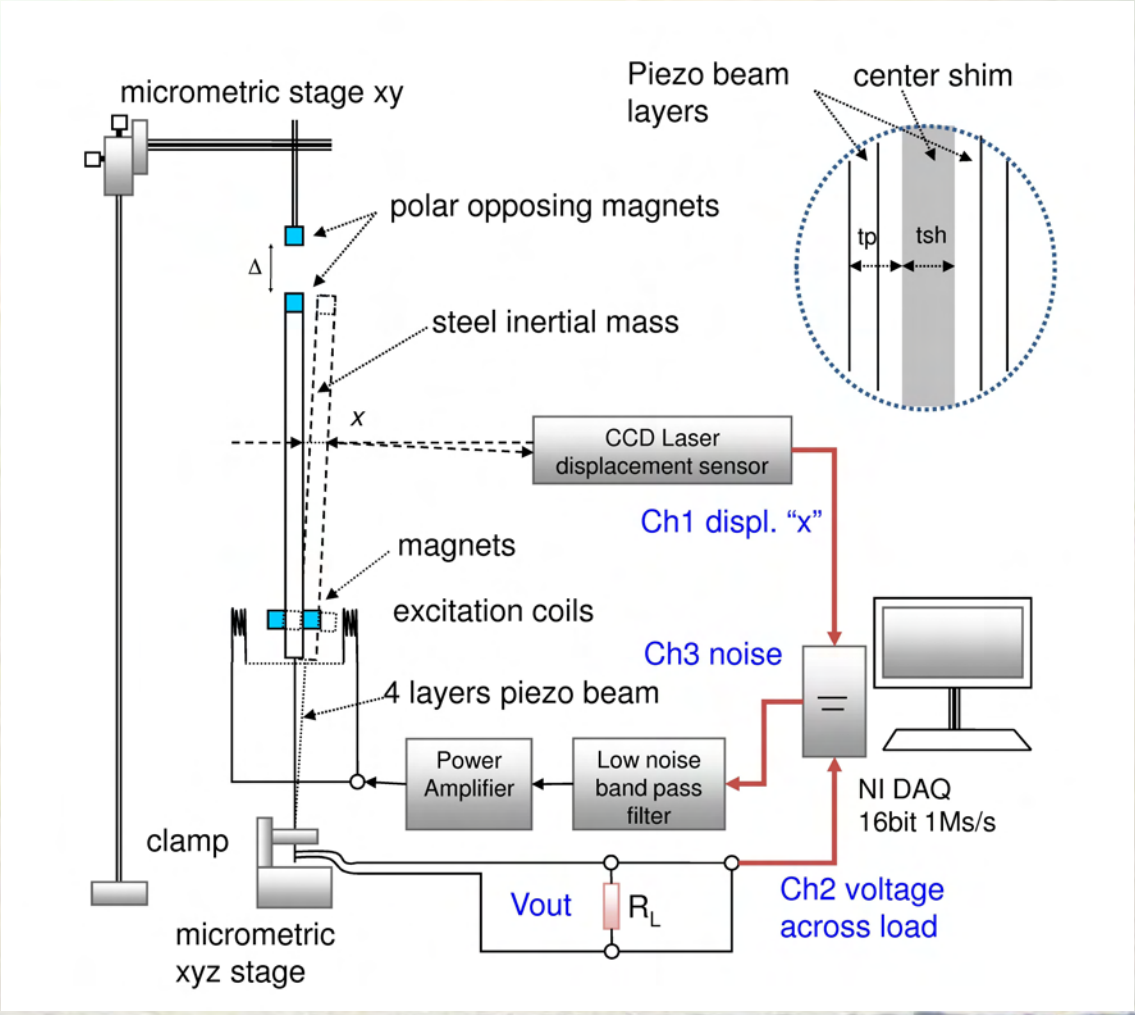




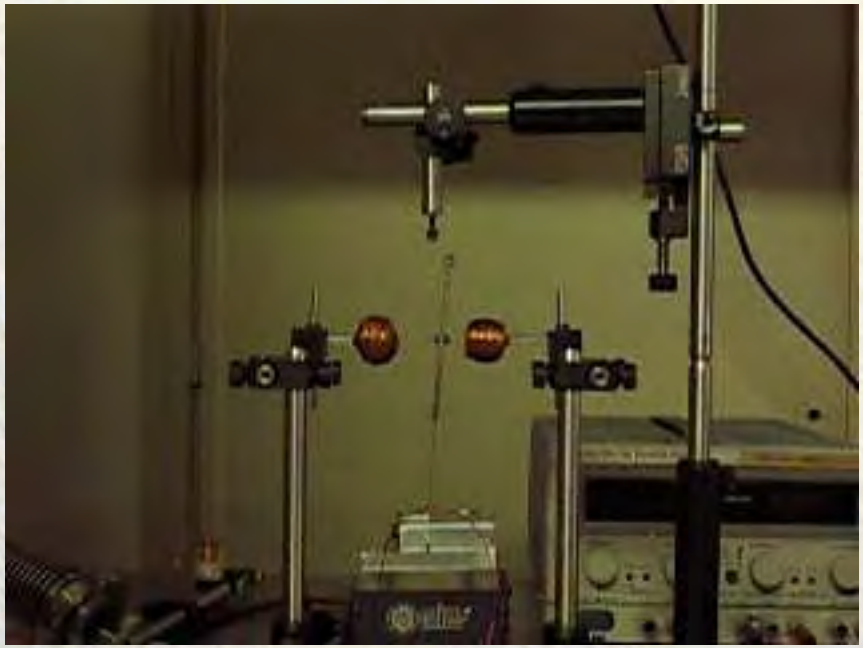
Vibrations energy harvesting

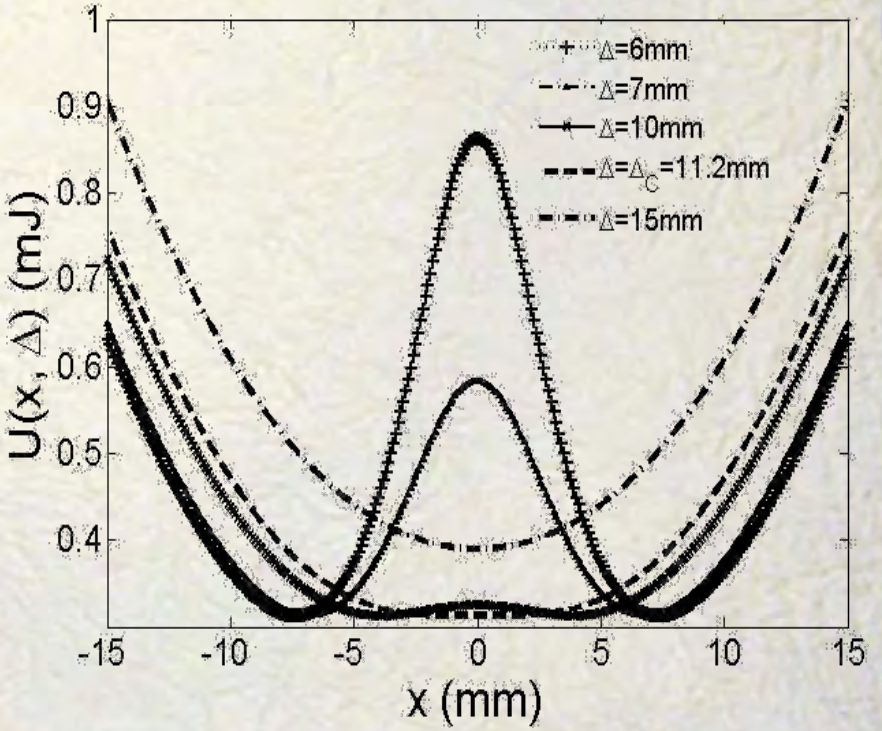
NON-Linear mechanical oscillators



Vibrations energy harvesting

NON-Linear mechanical oscillators



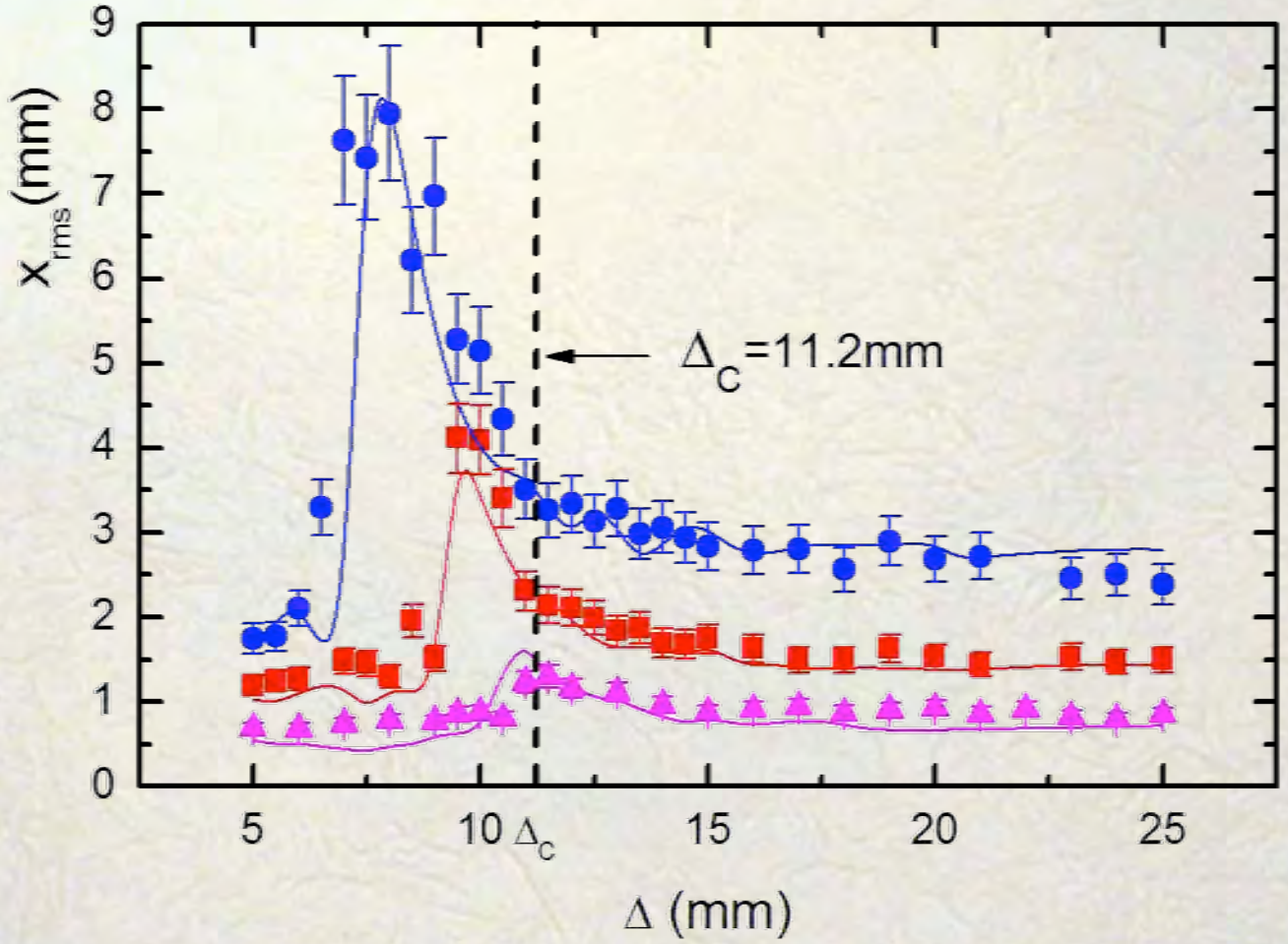


http://www.nipslab.org/node/1676

Nonlinear Energy Harvesting, F. Cottone; H. Vocca; L. Gammaitoni , Physical Review Letters, 102, 080601 (2009)

Vibrations energy harvesting

NON-Linear mechanical oscillators



Nonlinear Energy Harvesting, F. Cottone; H. Vocca; L. Gammaitoni , Physical Review Letters, 102, 080601 (2009)

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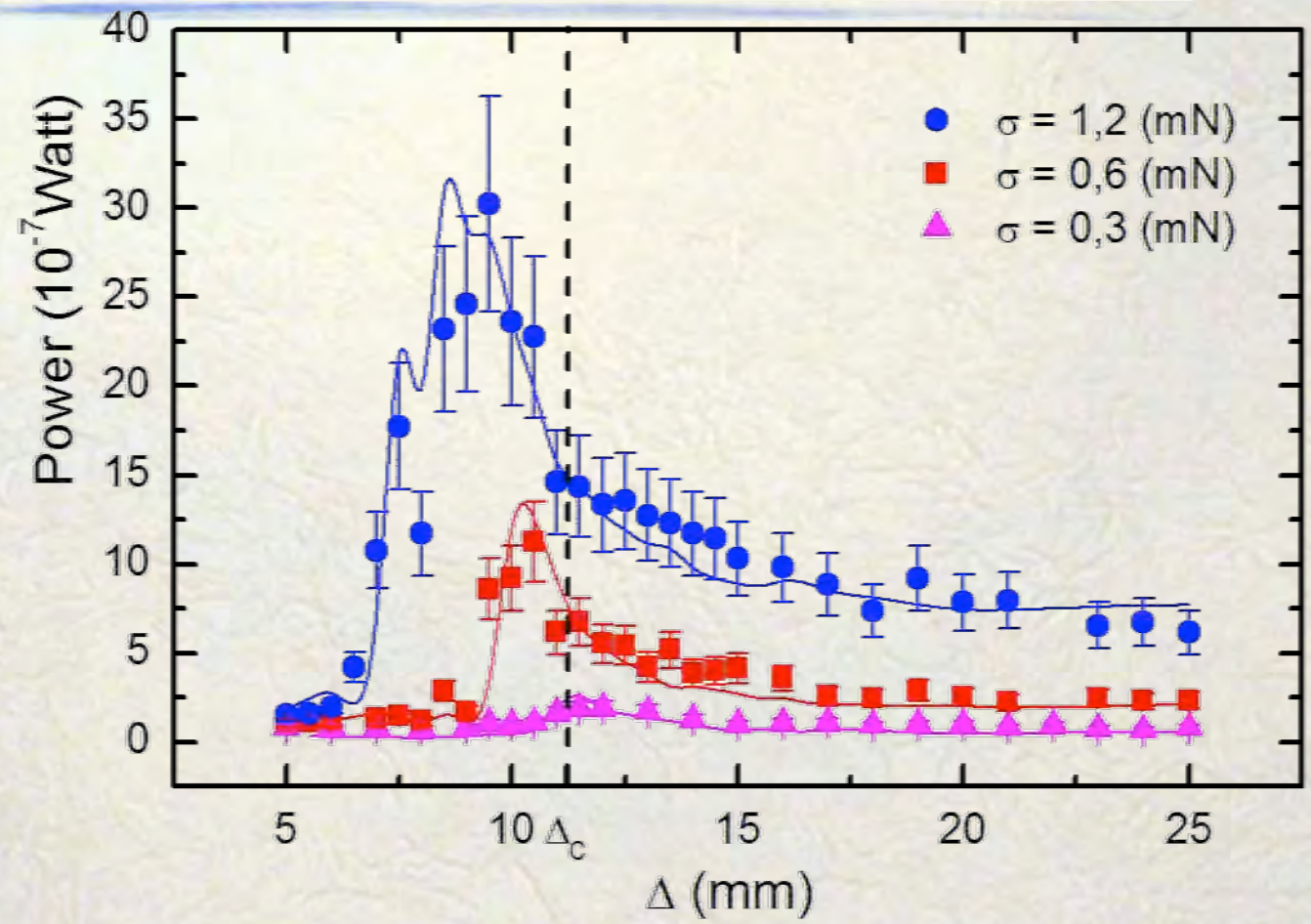

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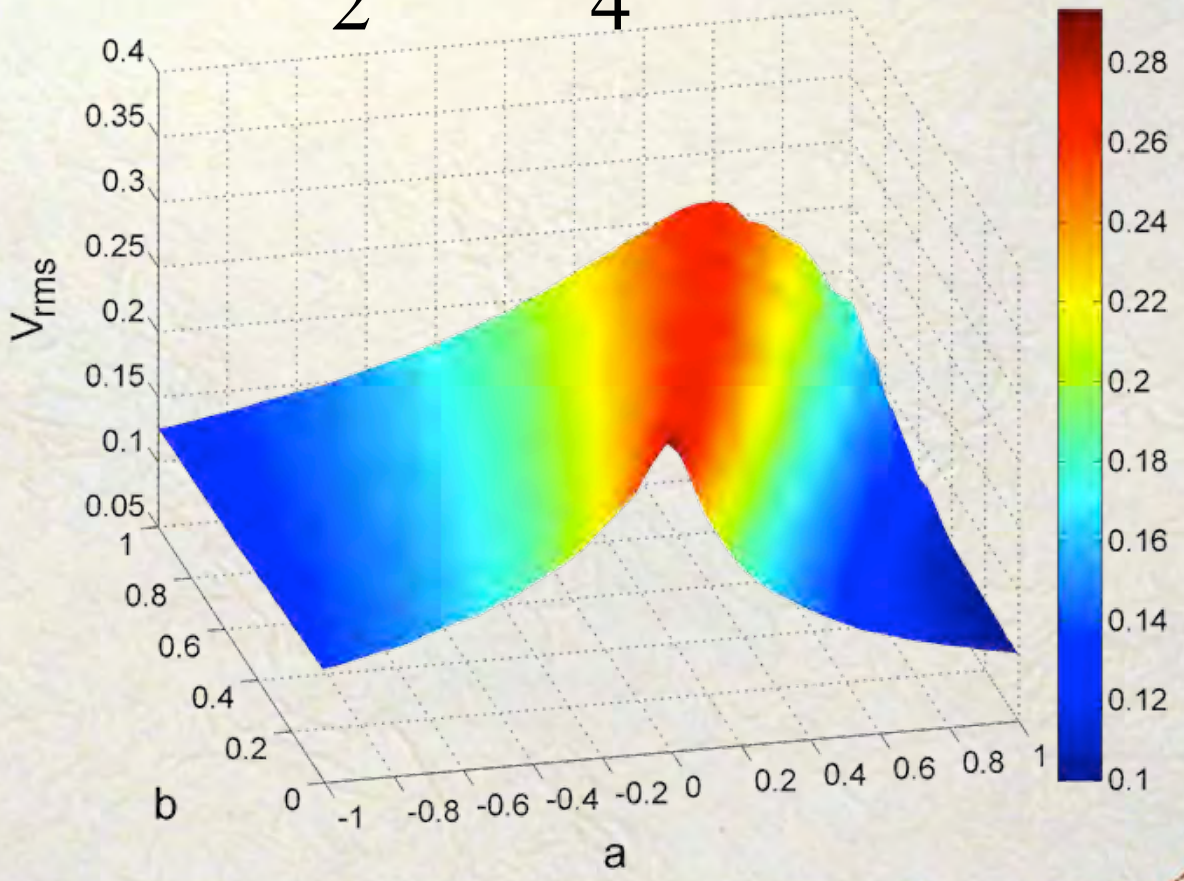
Noise energy harvesting

Non-linear systems

$$U(x) = -\frac{1}{2}ax^2 + \frac{1}{4}ax^4$$

Duffing potential



L. Gammaitoni, I. Neri, H. Vocca, Appl. Phys. Lett. 94, 164102 (2009)

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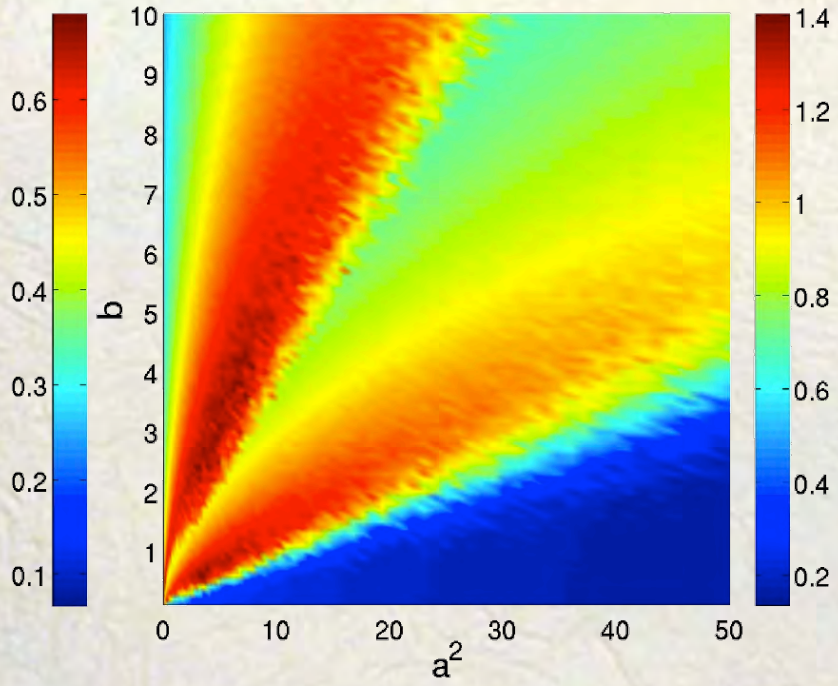

$$b_{MAX} = \frac{a^2}{4D\ \log(\tau_p)}$$

L. Gammaitoni, I. Neri, H. Vocca, Appl. Phys. Lett. 94, 164102 (2009)

To think about…

1) Non resonant (i.e. non-linear) mechanical oscillators can outperform resonant (i.e. linear) ones*

2) Non-linear systems are more difficult to treat

3) Bistability is not the only nonlinearity available… see:
L. Gammaitoni, I. Neri, H. Vocca, Appl. Phys. Lett. 94, 164102 (2009)

* **wisepower technology**, patent pending. For more info see: www.nipslab.org, www.wisepower.it

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