EnerHarv 2024

PSMA International Workshop | 26-28 June, 2024 | Perugia, Italy

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EnerHarv 2024 Workshop:

Fundamental physical limits in the energy consumption of IoT devices

Presented By –

Luca Gammaitoni

Università di Perugia

Wednesday, June 26, 2024

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University of Perugia (IT)
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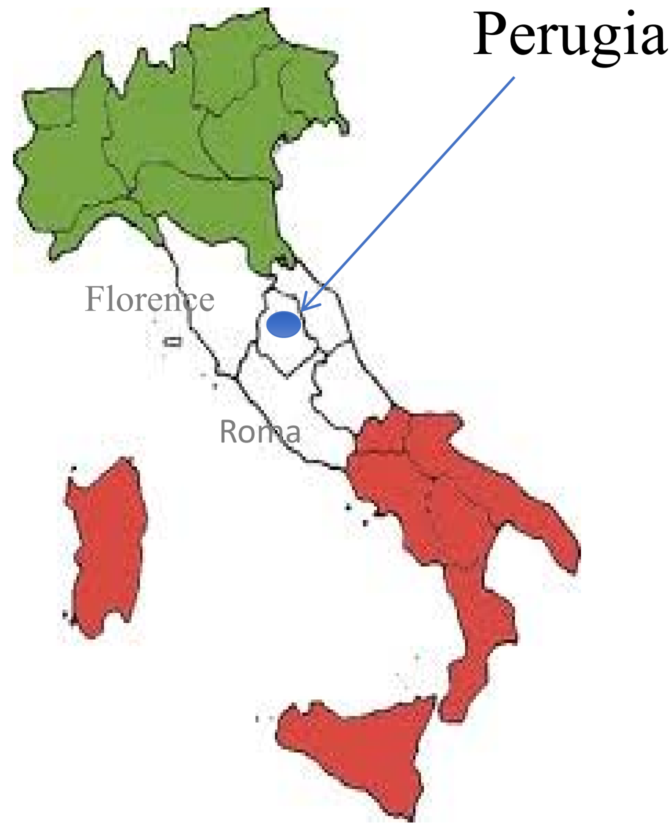

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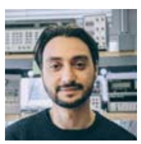

Cristina Diamantini, Francesco Cottone,
Igor Neri, Alessandro di Michele, Maurizio Mattarelli,
Giacomo Clementi, Giovanni Bellomo, Daviede Cianca
and Luca Gammaitoni

ICT-Energy ZEROPOWER

www.nipslab.org

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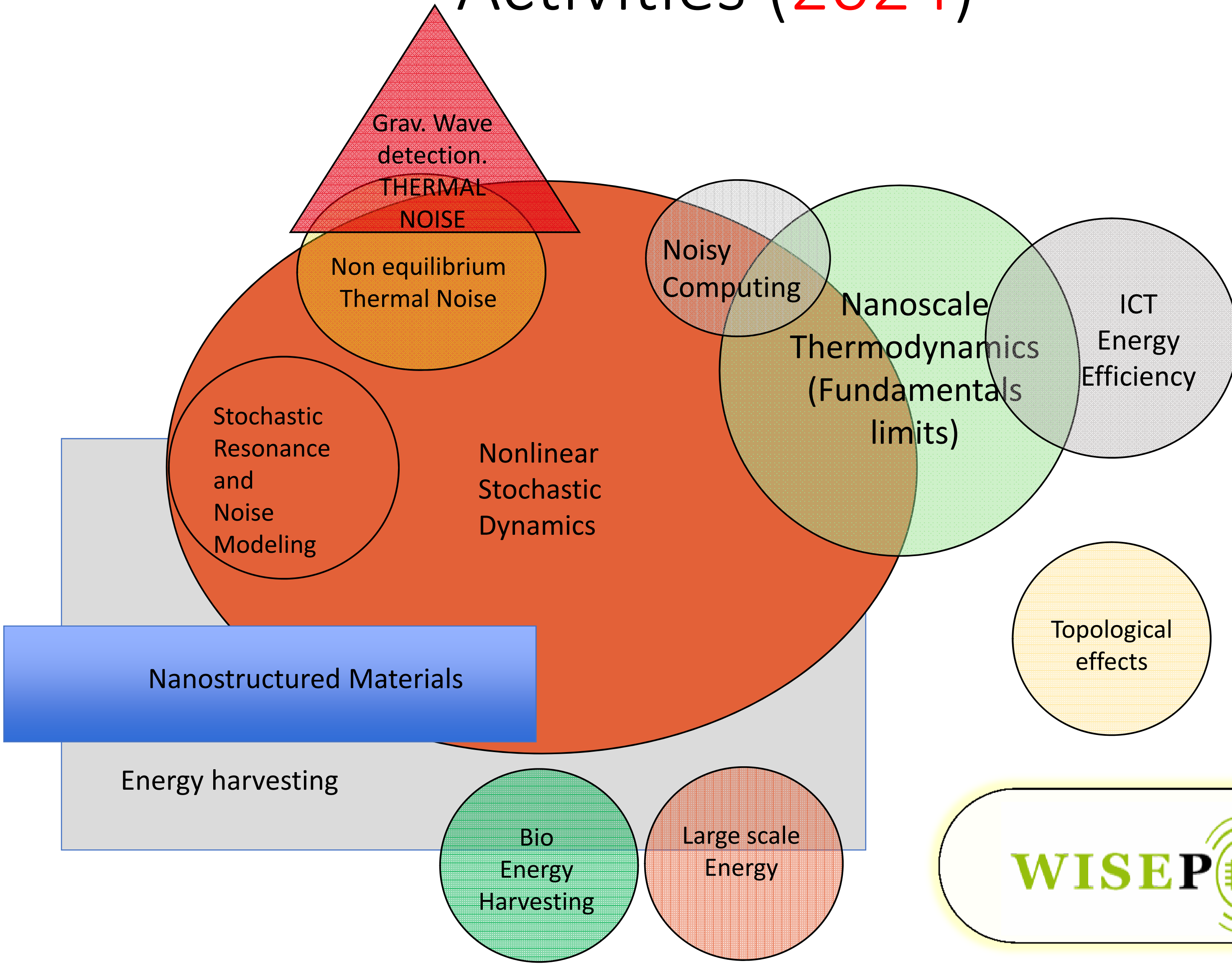
Activities (2024)



WISEPOWER

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NiPS Laboratory
Noise in Physical Systems

We are interested in noise and fluctuations.
Energy transformation processes at micro and nano scales.

EC Funded projects

2006-2009 EC (SUBTLE VIFP)
2010-2013 EC (NANOPOWER VIIFP)
2010-2013 EC (ZEROPOWER VIIFP)
2012-2015 EC (LANDAUER VIIFP)
2013-2016 EC (ICT-Energy VIIFP)
2015-2018 EC (Proteus H2020)
2017-2020 EC (OPRECOMP H2020)
2017-2022 EC (ENABLES H2020)
2022-2025 EC/PNRR (Vitality)

Constraints

Power significantly below 10 mW
Volumes significantly below 1 cm^3

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OVERVIEW

1. VITALITY

2. Energy harvesting and power management for IoT

3. Interesting directions for Energy Harvesting and the role of materials

Innovation, digitalisation and sustainability for the diffused economy in Central Italy

What is it?

It is the NextGenerationEU funded project aimed at establishing an **INNOVATION ECOSYSTEM** in CENTRAL ITALY

2022-2026

3 Regions in Central Italy
Abruzzo, Marche, Umbria

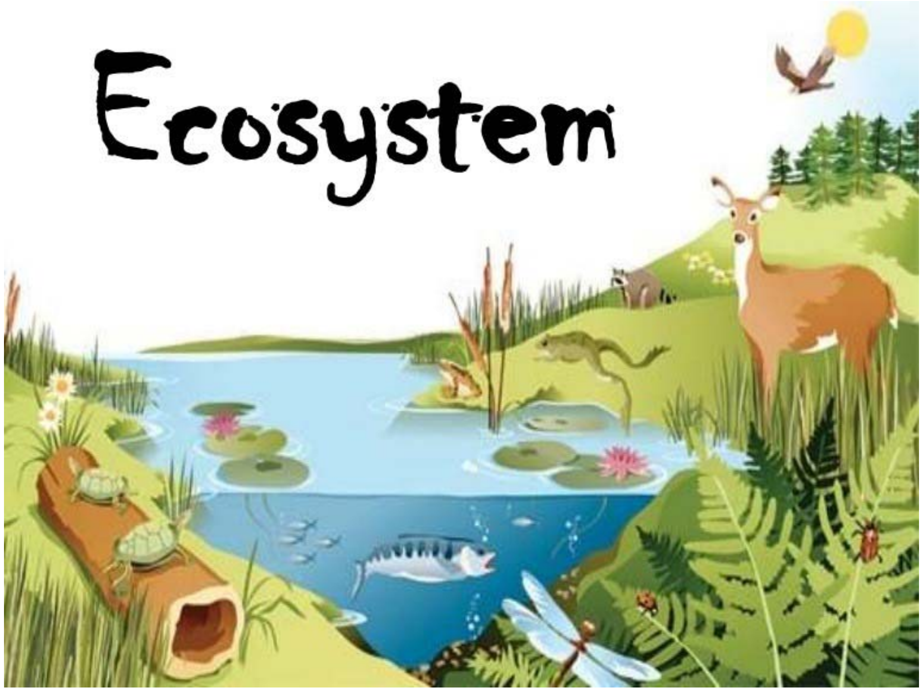
Path to development

1) Research

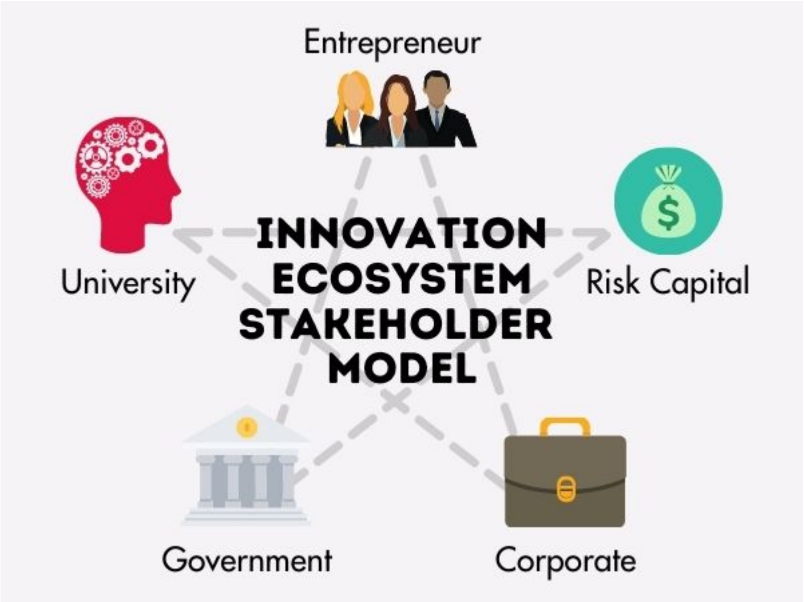
2) Innovation

3) Wealth

Biological ecosystem



Innovation ecosystem



VITALITY – HUB & SPOKE

Innovation, digitalisation and sustainability for the diffused economy in Central Italy

Hub

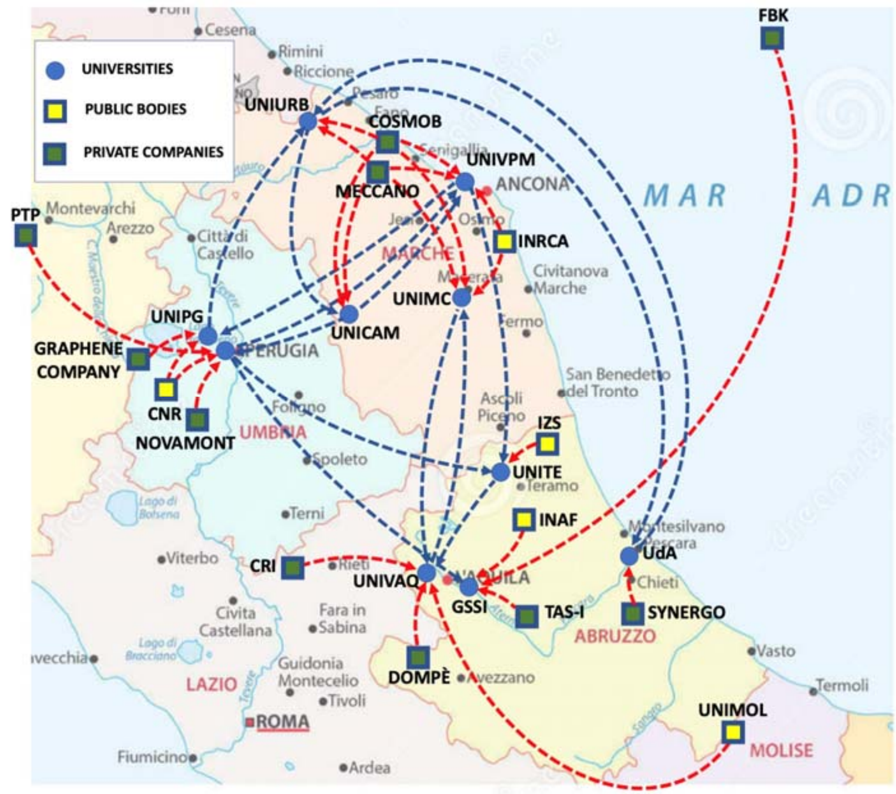
Hub composed of nine universities (**Università degli Studi dell'Aquila (lead)**, Gran Sasso Science Institute, Università degli Studi Chieti – Pescara, Università degli Studi di Teramo, Università Politecnica delle Marche, Università di Camerino, Università di Macerata, Università degli Studi di Urbino Carlo Bo, and Università degli Studi di Perugia).

Spokes

- 4 Spokes in the Abruzzo Region (at the Università degli Studi dell'Aquila, Gran Sasso Science Institute, Università degli Studi Chieti – Pescara and the Università degli Studi di Teramo)
- 4 Spokes the Marche Region (at the Università Politecnica delle Marche, Università di Camerino, Università di Macerata, Università degli Studi di Urbino Carlo Bo)
- 2 Spokes in the Umbria Region (at the Università degli Studi di Perugia).

Affiliates

- Public affiliates: Università degli Studi del Molise, istituto Nazionale di Astrofisica, CNR, Istituto Zooprofilattico Abruzzo-Molise, INRCA
- Private affiliates: Thales Alenia Space Italia SpA, CRI –Croce Rossa Italiana, Dompè S.p.a., Fondazione Bruno Kessler, COSMOB, Meccano, Novamont, Graphene Company, PTP, Synergo Group.



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PIANO NAZIONALE DI RIPRESA E RESILIENZA

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VITALITY – Cost and funding

Innovation, digitalisation and sustainability for the diffused economy in Central Italy

PROJECT COST

120.992.481,04 €

FUNDING

115.996.558,73 €

51,27% SUD

Research personnel	New researchers	Research equipment	SMEs support	Research sites	Other costs
41.606.721,75 €	18.522.800,22 €	20.226.028,06 €	15.341.720,00 €	3.700.000,00 €	16.599.288,70 €

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VITALITY

TOPICS

Abruzzo

MEGALITHIC Methods and technologies enhancing local specializations in **Health**, **Industry** and **Cybersecurity**	Università de L'AQUILA
ASTRA Advanced **Space** Technologies and Research Alliance	Gran Sasso Science Institute
Innovative **food** production: matching sustainability and quality of life	Università di Teramo
One-Health **Telemedicine** and **environment**	Università di Chieti-Pescara

Marche

Environmental, economic and social sustainability of **living** and **working environments**	Università Politecnica delle Marche
Innovation and safety of living environments in the **digital transition era**	Università di Camerino
Smart solutions and educational programs for **anti-fragility** and **inclusivity**	Università di Macerata
Innovative Therapeutic Approaches: New **Chemical Entities**, Biologics and **Drugs** Delivery	Università di Urbino

Umbria

Nanostructured material and devices	Università di Perugia
Bio based and bio compatible materials and devices	Università di Perugia

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Umbria

Nanostructured material and devices	Università di Perugia
Bio based and bio compatible materials and devices	Università di Perugia

SPOKE 9 Nanostructured materials and devices

Objectives

WP1 **Nanomaterials: design, production, characterization**	• Design of innovative nanomaterials • Production of innovative nanomaterials • Characterization of innovative nanomaterials
WP2 **Innovative devices for industrial applications**	• NEMS/MEMS devices and systems • Energy aimed applications • Communication devices for quantum computing
WP3 **Graphene & carbon-based materials**	• Graphene • Carbon based materials • Micronization processes
WP4 **Education, dissemination and TT**	• Education activities • Dissemination activities • Technology transfer

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SPOKE 9 Nanostructured materials and devices

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UNICAM

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2) Energy Harvesting and power management for IoT

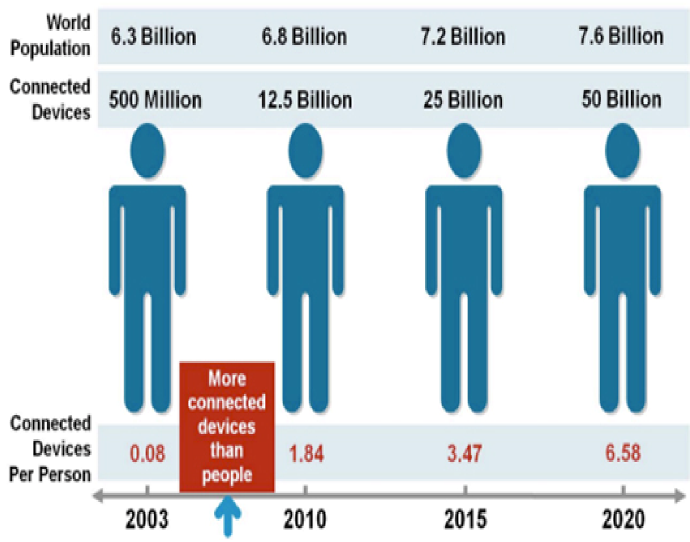
Sensing and computing are very important in our society and their impact on our everyday life can be hardly overestimated.

April 4, 2005

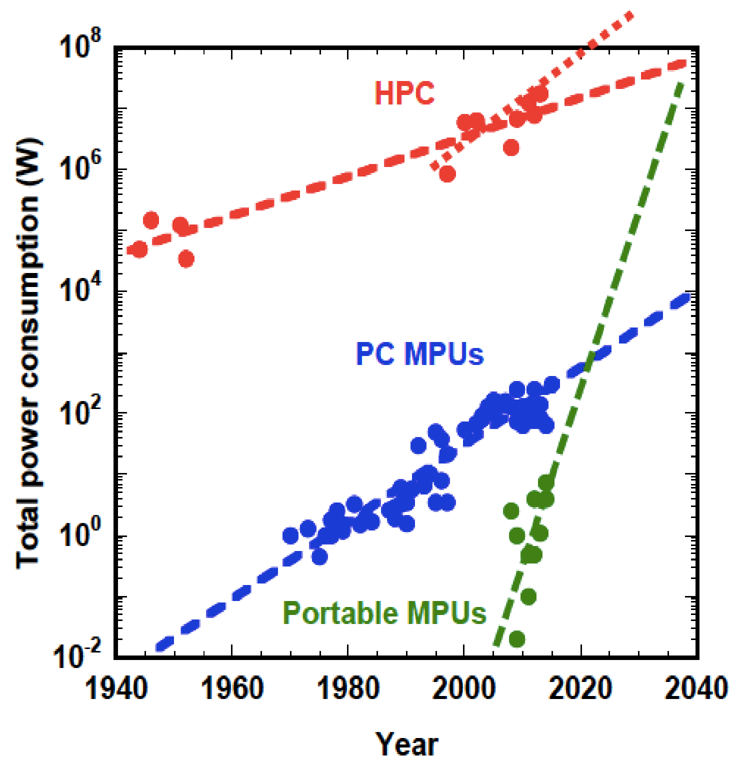
March 13, 2013

Fact

Mobile computing is growing exponentially. The so called Internet of Things scenario requires reliable low-power devices capable of computing and communication.



Source: Cisco IBSG, April 2011



Need for autonomous power

Source: D. Paul, ICT-Energy Research Agenda, 2015

Why the Internet of Things scenario has not been fully realized yet?

Energy required to operate the electronic devices

We need to bridge the gap by acting on both arrows

Necessary knowledge is in the **micro-scale energy management**

Energy available from various portable sources

Some modeling

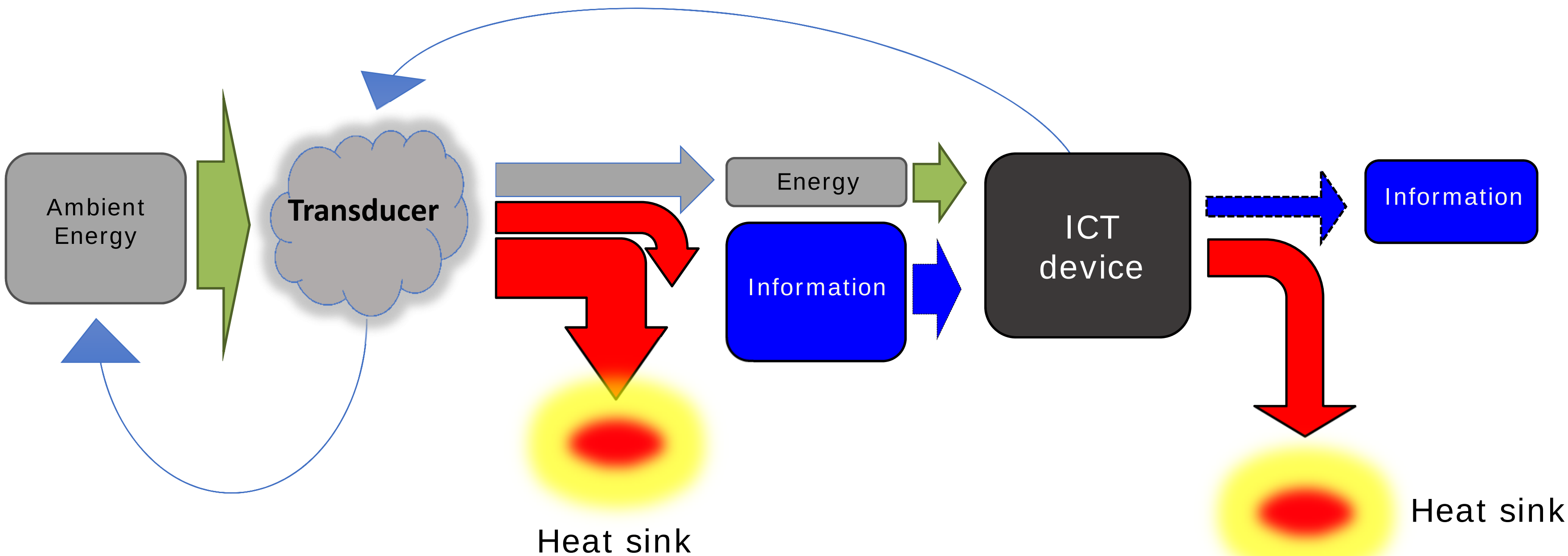
The device powering issue:

1) How much energy is needed to power a device ?

2) Where does the device get the needed energy ?

We consider devices at MEMS scale and below

We consider "ICT devices": i.e. devices mainly devoted to computing task

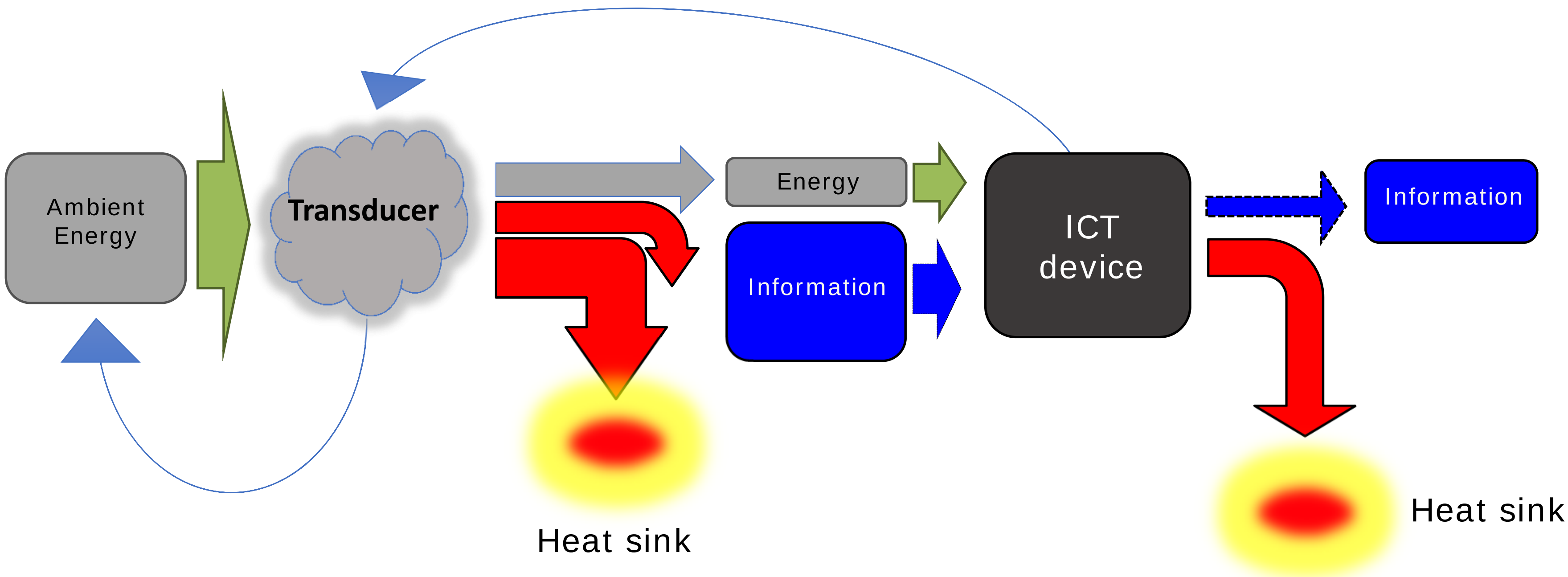


An ICT device is an info-thermal machine that inputs information and energy (under the form of work), processes both and outputs information and energy (mostly under the form of heat).

Some interesting questions:

Why all the energy ends up in heat? What does it mean “energy dissipation”? Can be avoided?

What is the role of information? Is this a physical quantity that affects the energy transformations?



We need a physical model…

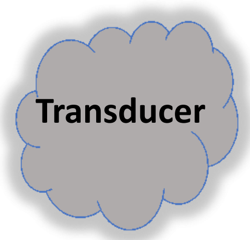
Two physical systems:

They transform energy

They have many d.o.f. (presence of fluctuations)

They are operated in a changing environment

~~Thermodynamics~~ ~~Statistical mechanics~~ Non-equilibrium statistical mechanics



In this framework we can describe the device behavior in terms of few relevant d.o.f. via a procedure called "adiabatic elimination" or "coarse graining approach": we exchange the dynamics of a *not small isolated system* with *small not isolated system.*

Let's see an example…

Two physical systems whose dynamical behavior can be described in the framework of non-equilibrium statistical mechanics.

Langevin equation approach

$$m\ddot{x} = -\gamma\dot{x} + \zeta + F_{ext}$$

$$F_{ext} = -\frac{dU(x,t)}{dx} + \zeta_z$$

Deterministic force depending on *x, t*

Random force depending on *t*

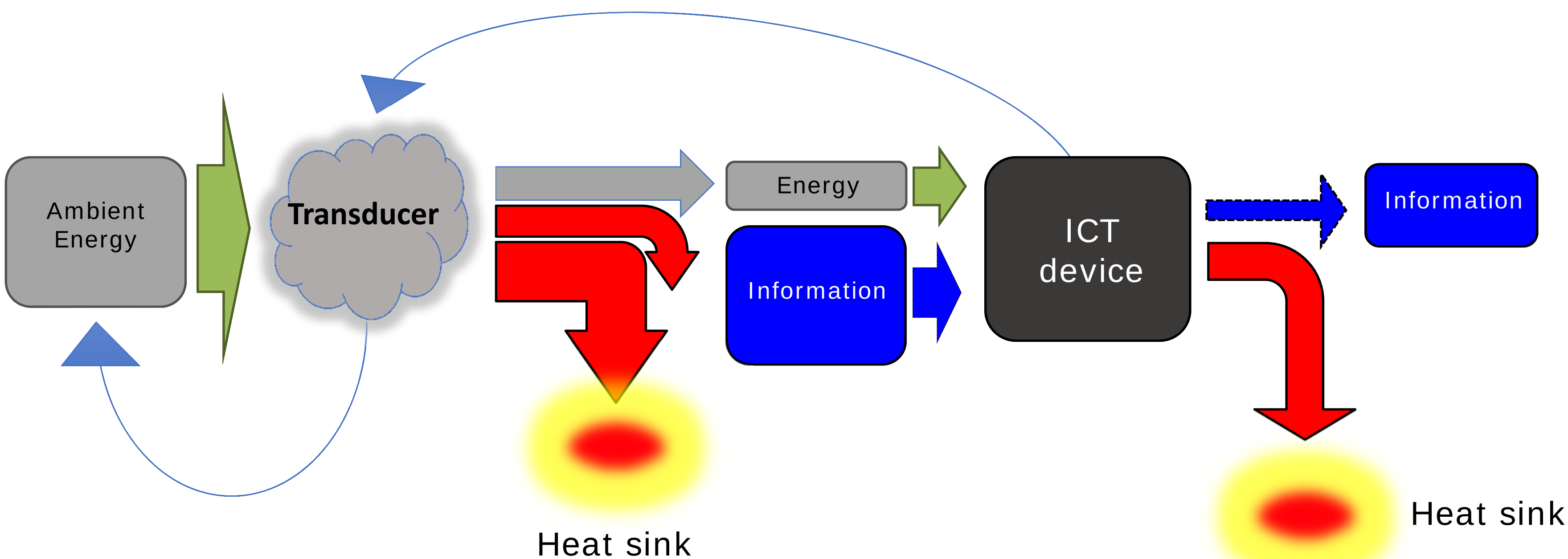
If $F_{ext} >> \zeta$ then the thermal noise contribution can be ignored

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

The device powering issue:

1) How much energy is needed to power a device ?

2) Where does the device get the needed energy ?

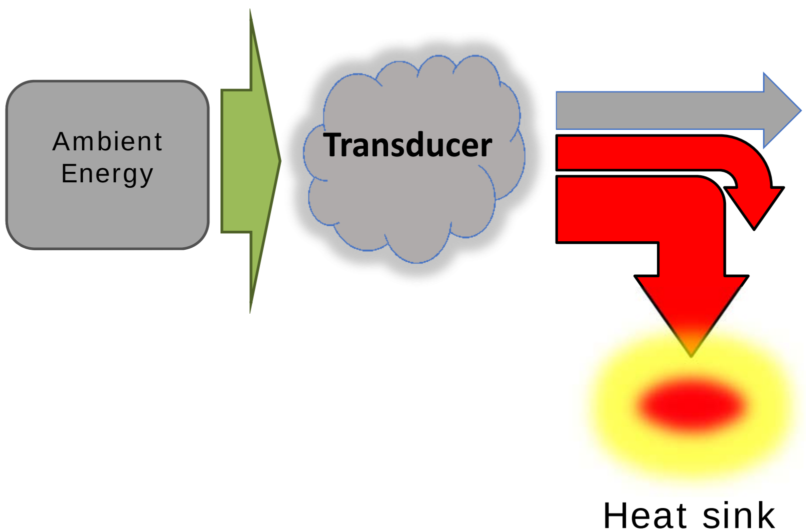


The device powering issue:

1) How much energy is needed to power a device ?

2) Where does the device get the needed energy ?

Let’s focus on the energy transformation process

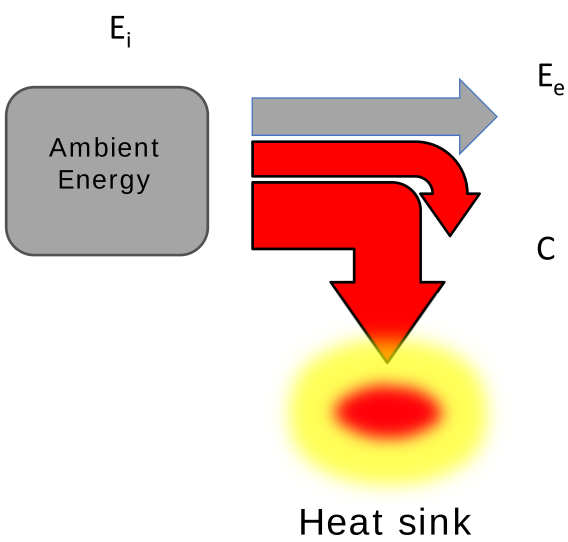


Clearly this energy is obtained from the ambient…

The device powering issue:

1) How much energy is needed to power a device ?

2) Where does the device get the needed energy ?



Energy is conserved….

$E_e = E_i - C$

Question: can we make C = 0 ?

C is the energy dissipated during the transformation.

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

C=C(γ) and γ is associated with the relaxation to equilibrium and depends on the characteristics of the device/material.

The device powering issue:

1) How much energy is needed to power a device ?

2) Where does the device get the needed energy ?

C is the energy dissipated during the transformation.

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

The usual solution is to go very slow, i.e. to minimize $\dot{x}$

Good news: In principle there is no physical law that forbids to make C = 0

Bad news: This affects the power we can use in the device

C=C(γ) can be a function of time and change with the dissipation process.
Viscous damping, thermo-eleastic damping, structural damping, …

Generalized Langevin equation

$$m\ddot{x} = -\frac{dU(x,t)}{dx} + \zeta_z - \int_{-\infty}^{t} \gamma(t-\tau)\,\dot{x}\,d\tau + \zeta$$

3) Interesting directions for Energy Harvesting and the role of materials

Sources of energy

Thermal gradients

Kinetic energy
at micro scale: random vibrations / noise, **Thermal noise**
Acoustic noise, **Seismic noise**, **Ambient noise** (wind, pressure fluctuations, …), **Man made vibrations** (human motion, machine vibrations,…)

Electromagnetic radiation
RF radiation, solar, …

Chemical/biological energy

All different for intensity, spectrum, statistics

The source of energy

Kinetic energy

at micro scale: 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

Vibration database: RealVibrations

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

realvibrations.nipslab.org

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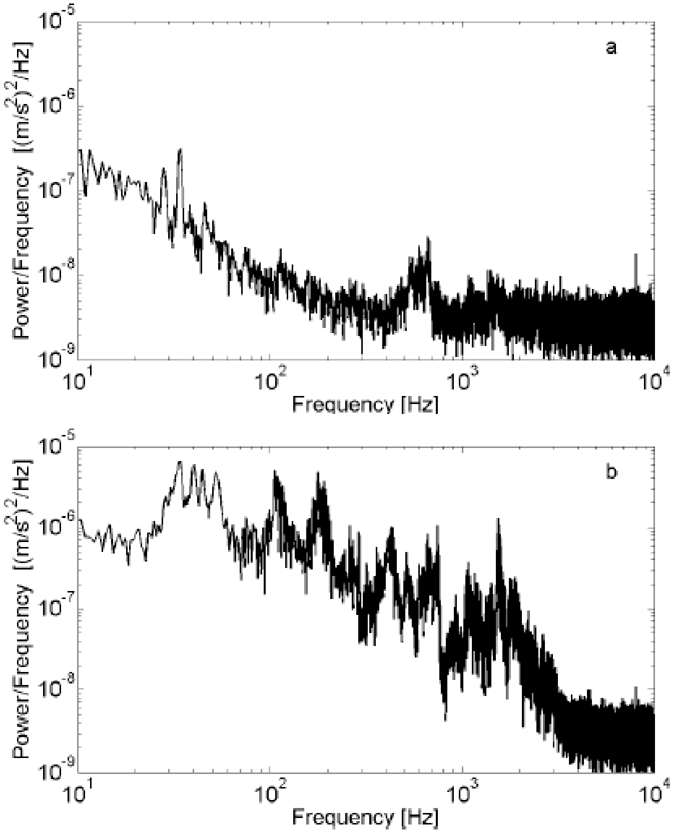
Signal presentation:

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

Bridge vibrations



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

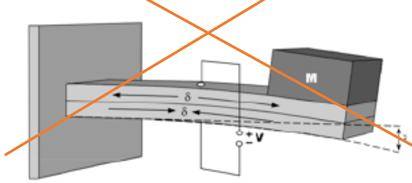
Vibrations energy harvesting

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

The oscillator dynamics

$U(x)$ Represents the Energy stored

$$U(x) = \frac{1}{2}kx^2$$



$$U(x) \neq \frac{1}{2}kx^2$$

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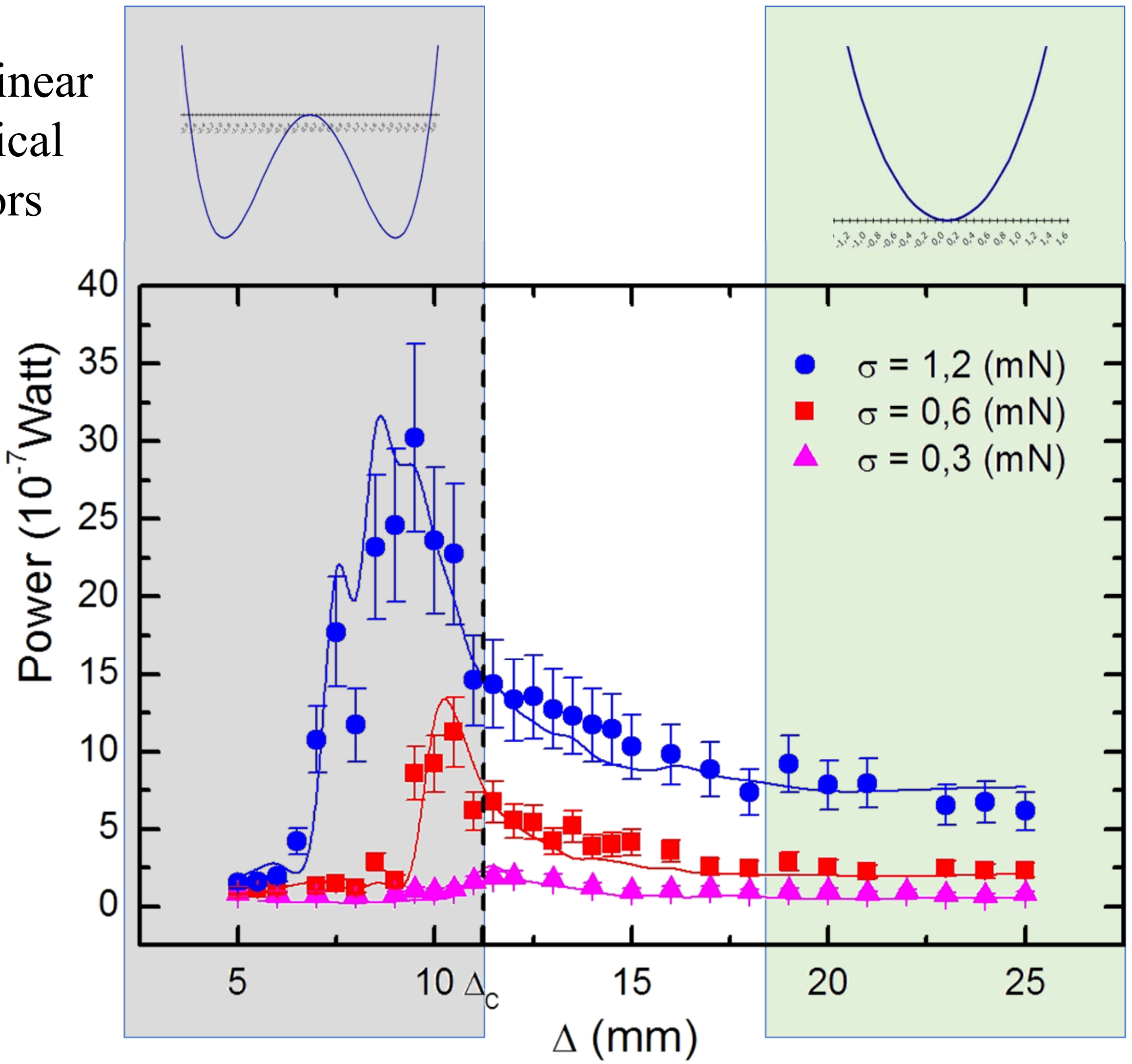
Power response

NON-Linear mechanical oscillators

Linear mechanical oscillators



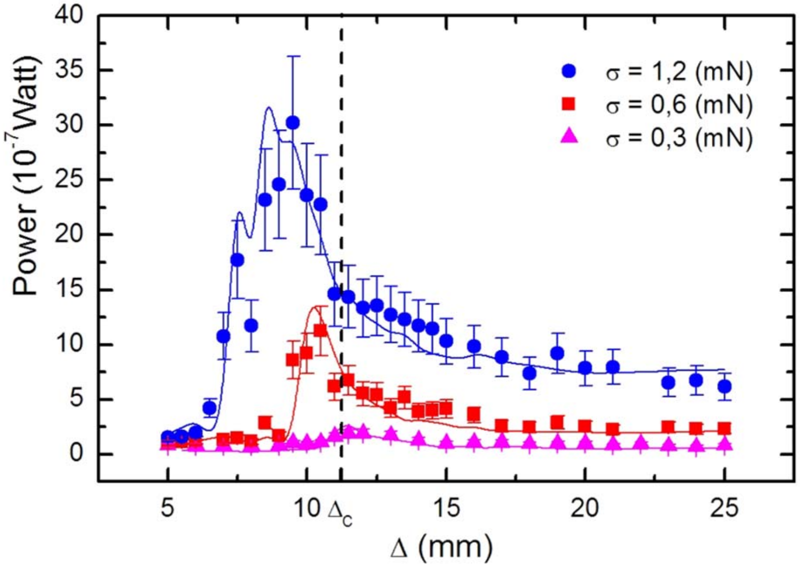
PRL **102,** 080601 (2009) PHYSICAL REVIEW LETTERS week ending 27 FEBRUARY 2009

Nonlinear Energy Harvesting

F. Cottone,* H. Vocca, and L. Gammaitoni†

NiPS Laboratory, Dipartimento di Fisica, Universitá di Perugia, and Instituto Nazionale di Fisica Nucleare, Sezione di Perugia, I-06100 Perugia, Italy

(Received 18 September 2008; published 23 February 2009)



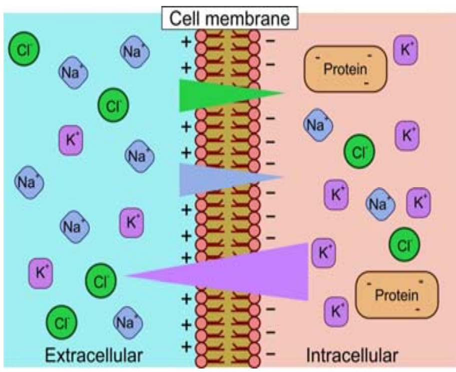
Nonlinear Energy Harvesting, F. Cottone; H. Vocca; L. Gammaitoni, Physical Review Letters, 102, 080601 (2009)

The role of materials

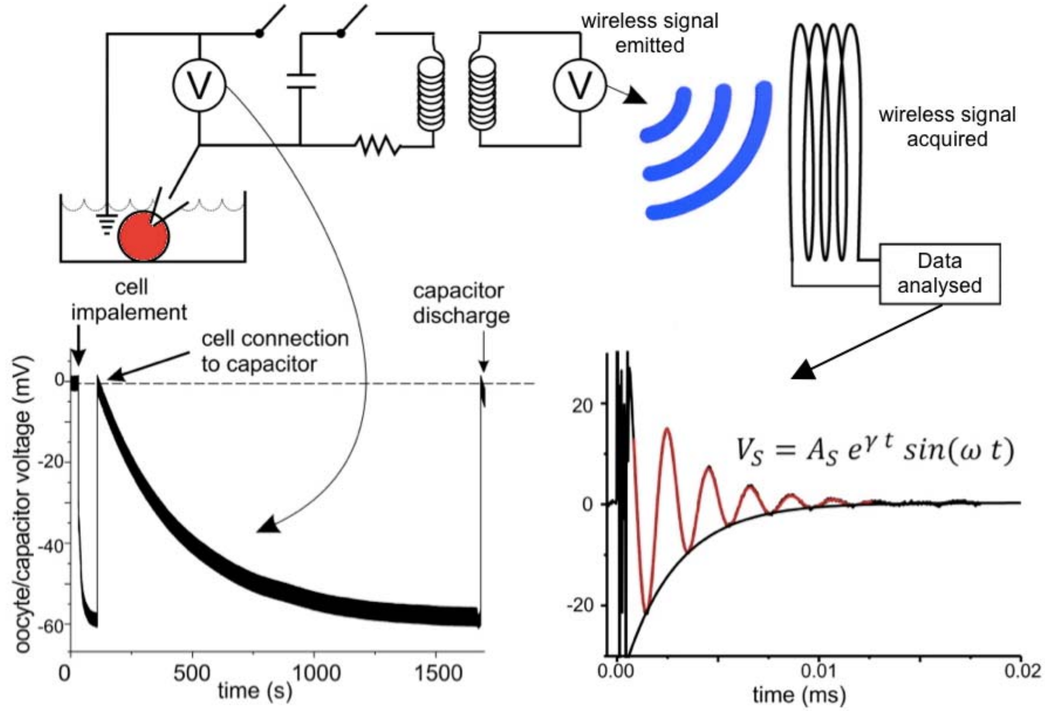
$$
\begin{cases}
m\ddot{x} = -\dfrac{dU(x)}{dx} - \gamma\dot{x} - K_V V + \zeta_z \\
\dot{V} = K_c\dot{x} - \dfrac{1}{\tau_p} V
\end{cases}
$$

The material properties

Energy Harvesting in the Bio realm



Energy harvesting from a bio cell
L Catacuzzeno, F Orfei, A Di Michele, L Sforna, F Franciolini and L Gammaitoni
Nano energy 56, 823-827, 2019



Contents lists available at ScienceDirect

Nano Energy

journal homepage: www.elsevier.com/locate/nanoen

Full paper

Energy harvesting from a bio cell

L. Catacuzzeno[a,*], F. Orfei[b], A. Di Michele[b], L. Sforna[c], F. Franciolini[a], L. Gammaitoni[b,*]

Conclusion

Take-home message:

1) Focusing **only** on **energy harvesting** produces misconception. The focus should be on **energy transformation** processes and the **materials** matter.

2) Both ends of the gap (harvesting and dissipation) should be addressed if we want to move from labs to market.

Q & A

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PSMA International Workshop | 26-28 June, 2024 | Perugia, Italy

Thanks very much for your time and attention!

Questions/comments???

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