Energy harvesting IV – nonlinear EH

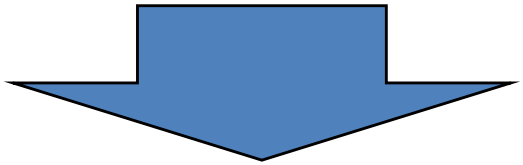
Luca Gammaitoni

NiPS Laboratory, University of Perugia

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

Nonlinear noise harvesting

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

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

The oscillator dynamics

Focus on the potential energy

NON-Linear mechanical oscillators

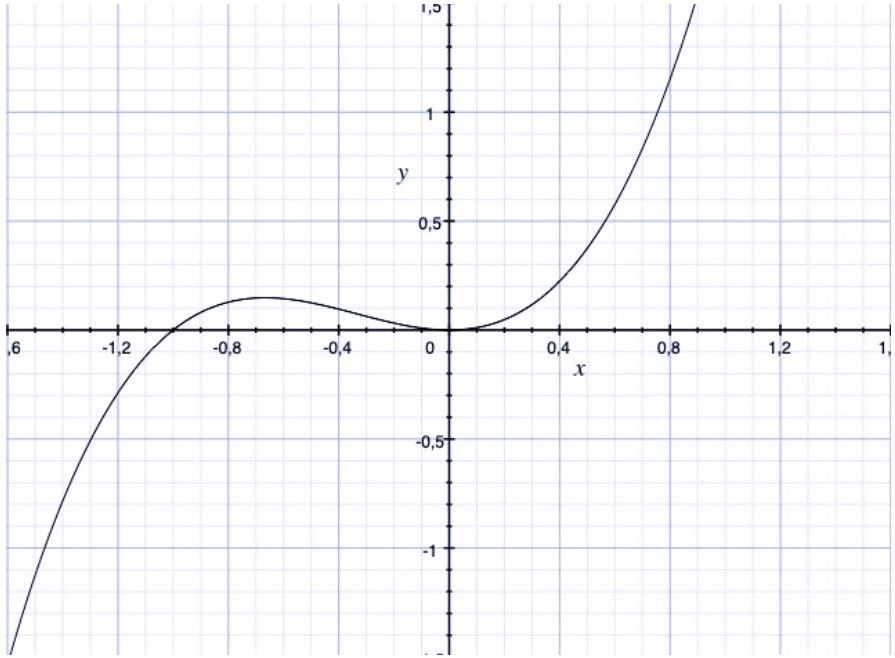
$$U(x) \neq \frac{1}{2}ax^2$$

Nonlinear noise harvesting

NON-Linear mechanical oscillators

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

$$U(x) = a\,x^2 + bx^3$$



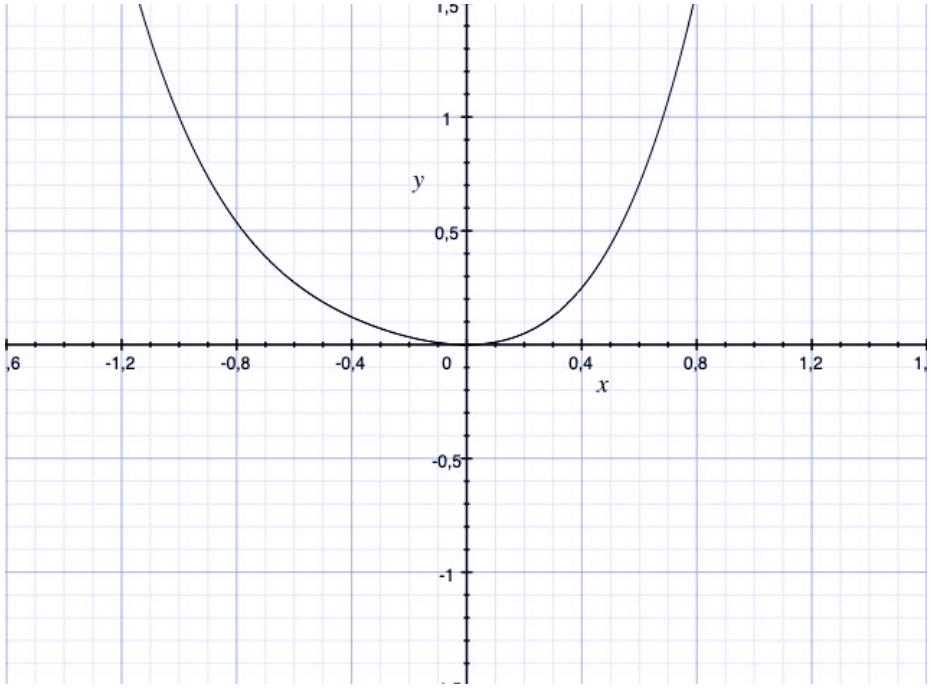
Potenziale non confinante !!!

Nonlinear noise harvesting

NON-Linear mechanical oscillators

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

$$U(x) = a\,x^2 + bx^3 + cx^4$$



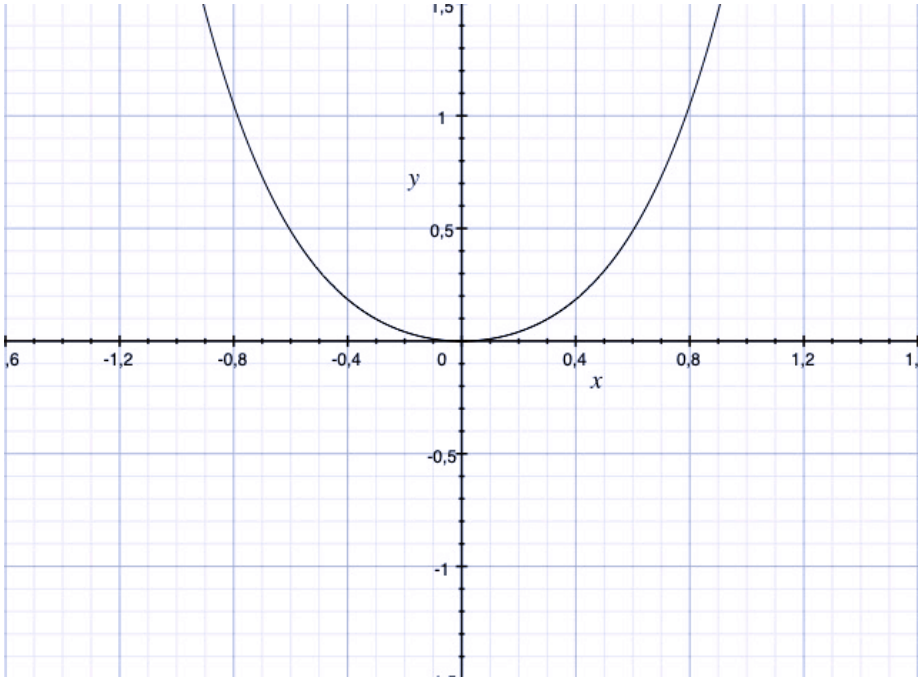
Potenziale confinante ma asimmetrico

Nonlinear noise harvesting

NON-Linear mechanical oscillators

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

$$U(x) = a\, x^2 + c x^4$$



Potenziale confinante e simmetrico

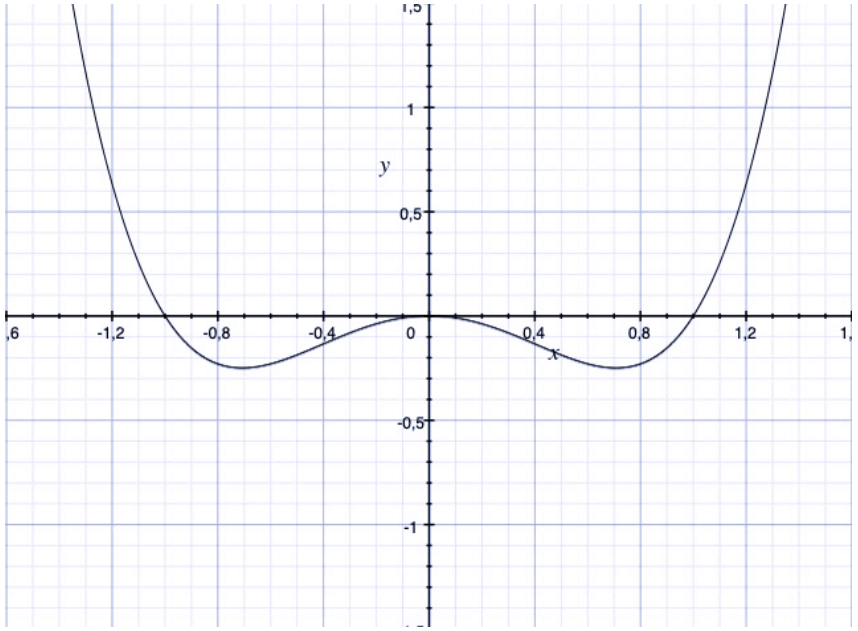
Nonlinear noise harvesting

NON-Linear mechanical oscillators

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

$$U(x) = a\, x^2 + c x^4$$

If a<0 we have bistability

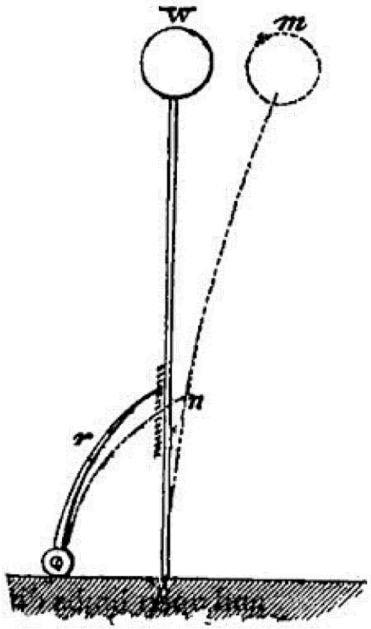


Potenziale confinante e simmetrico

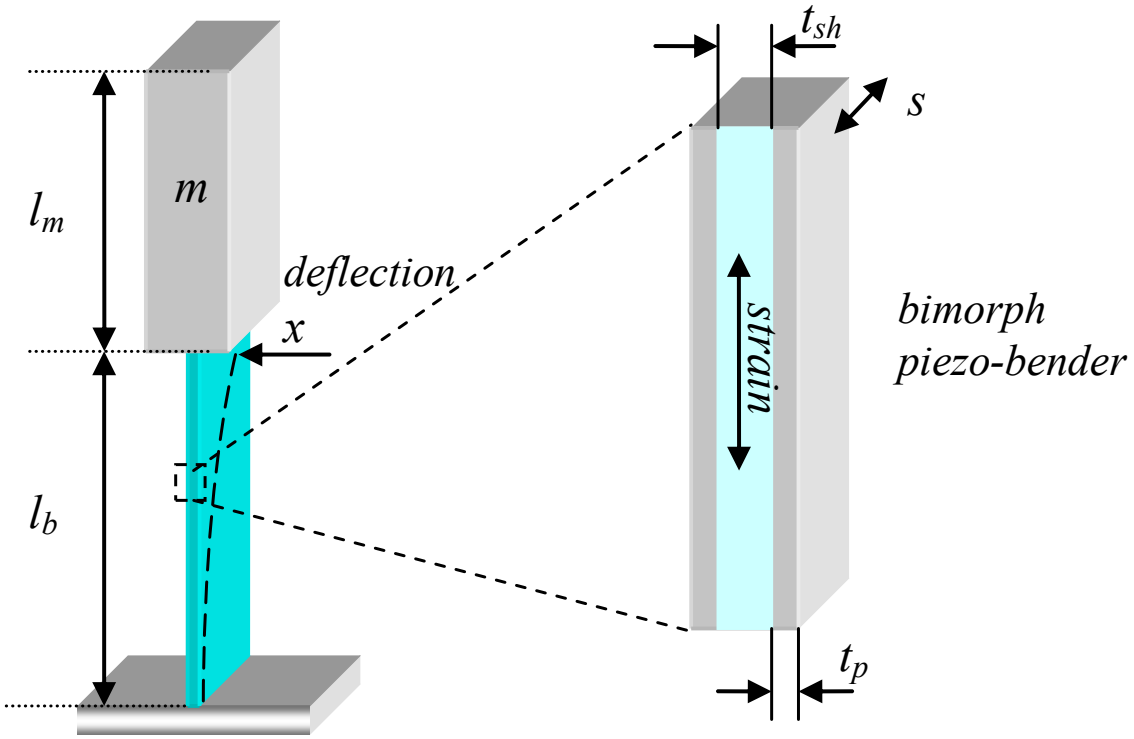
Nonlinear noise harvesting

Example…

Inverted pendulum



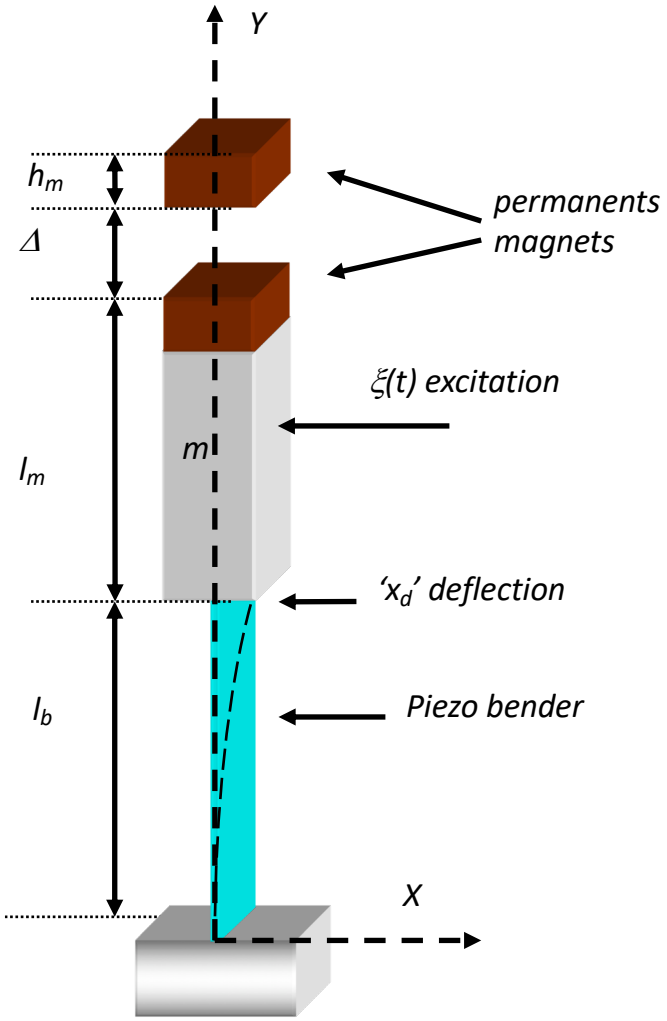
This is a linear system !

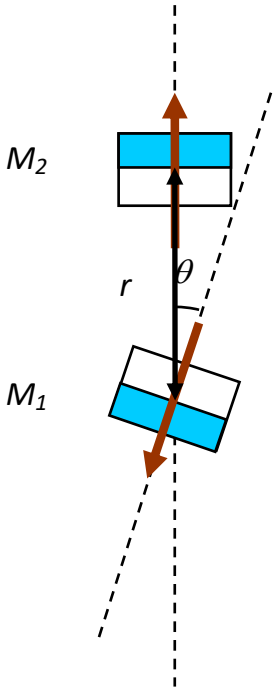


F. Cottone, PhD Thesys, Perugia 2007

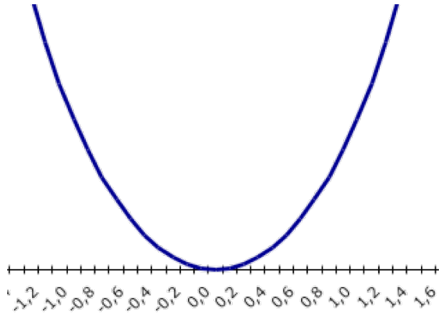
Nonlinear noise harvesting

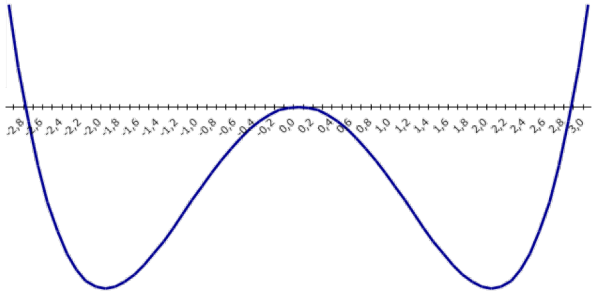
NON-Linear Inverted pendulum





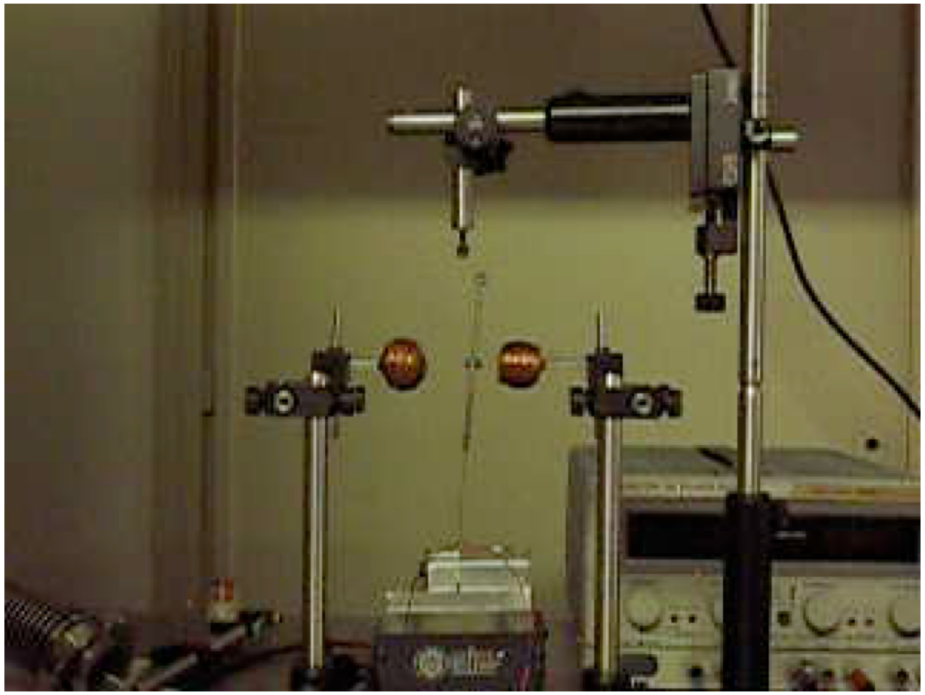
b)

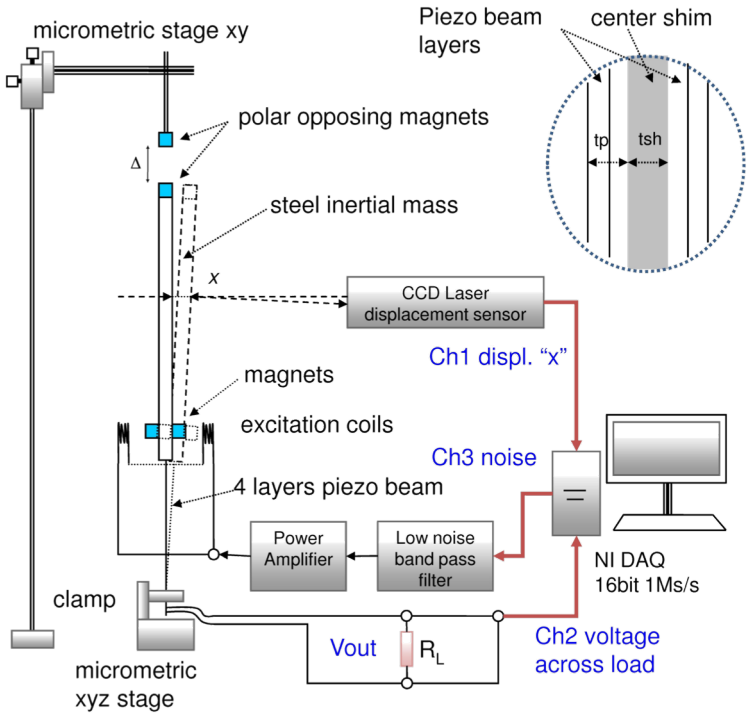




Nonlinear noise harvesting

NON-Linear mechanical oscillators





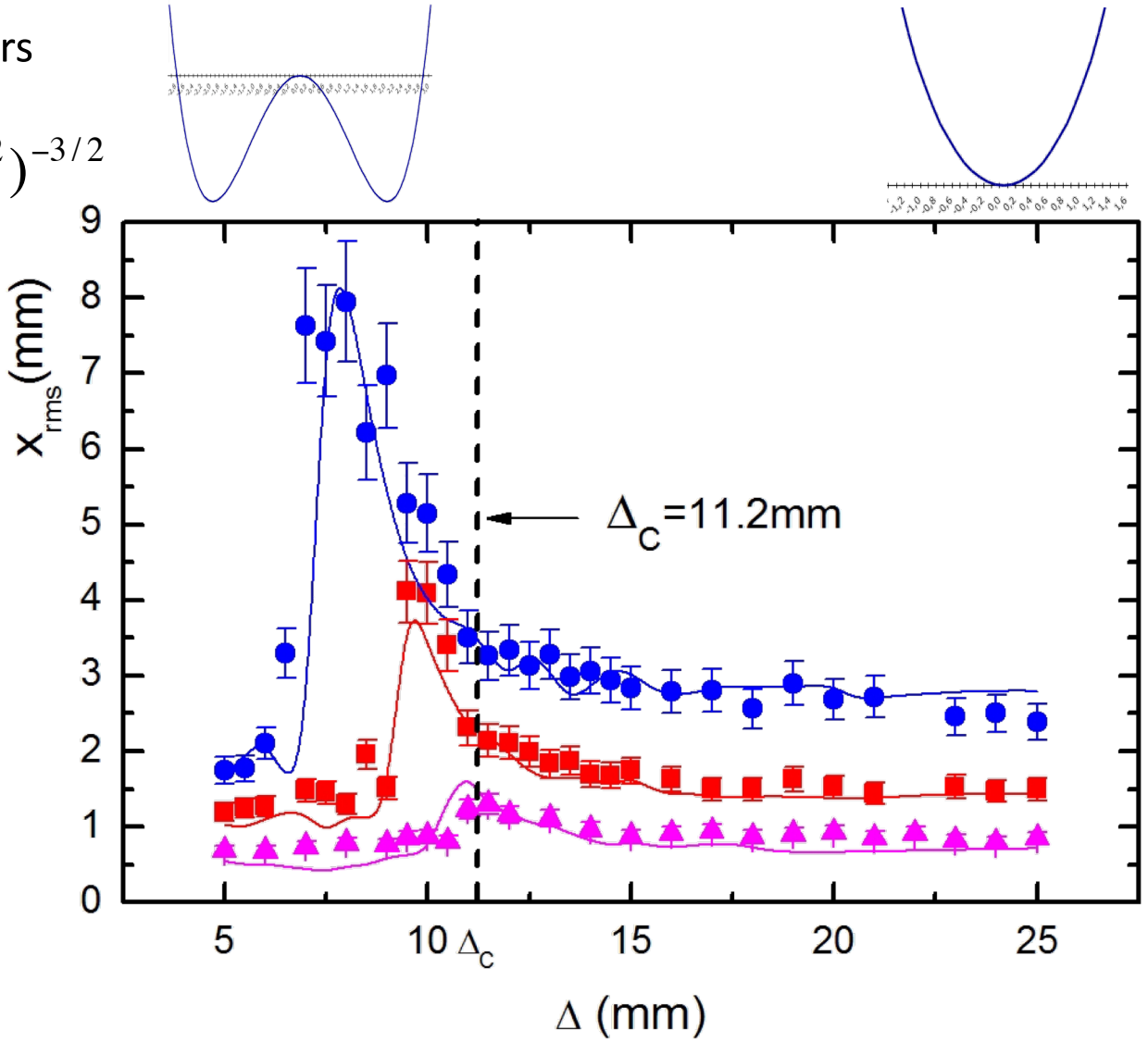
http://www.nipslab.org/node/1676

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

Nonlinear noise harvesting

NON-Linear mechanical oscillators

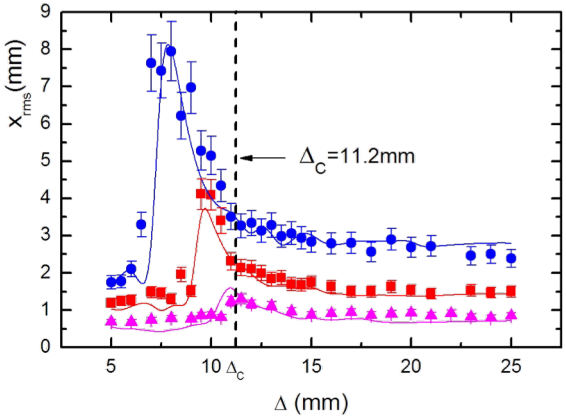
$$U(x) = \frac{1}{2} k_e x^2 + (Ax^2 + B\Delta^2)^{-3/2}$$

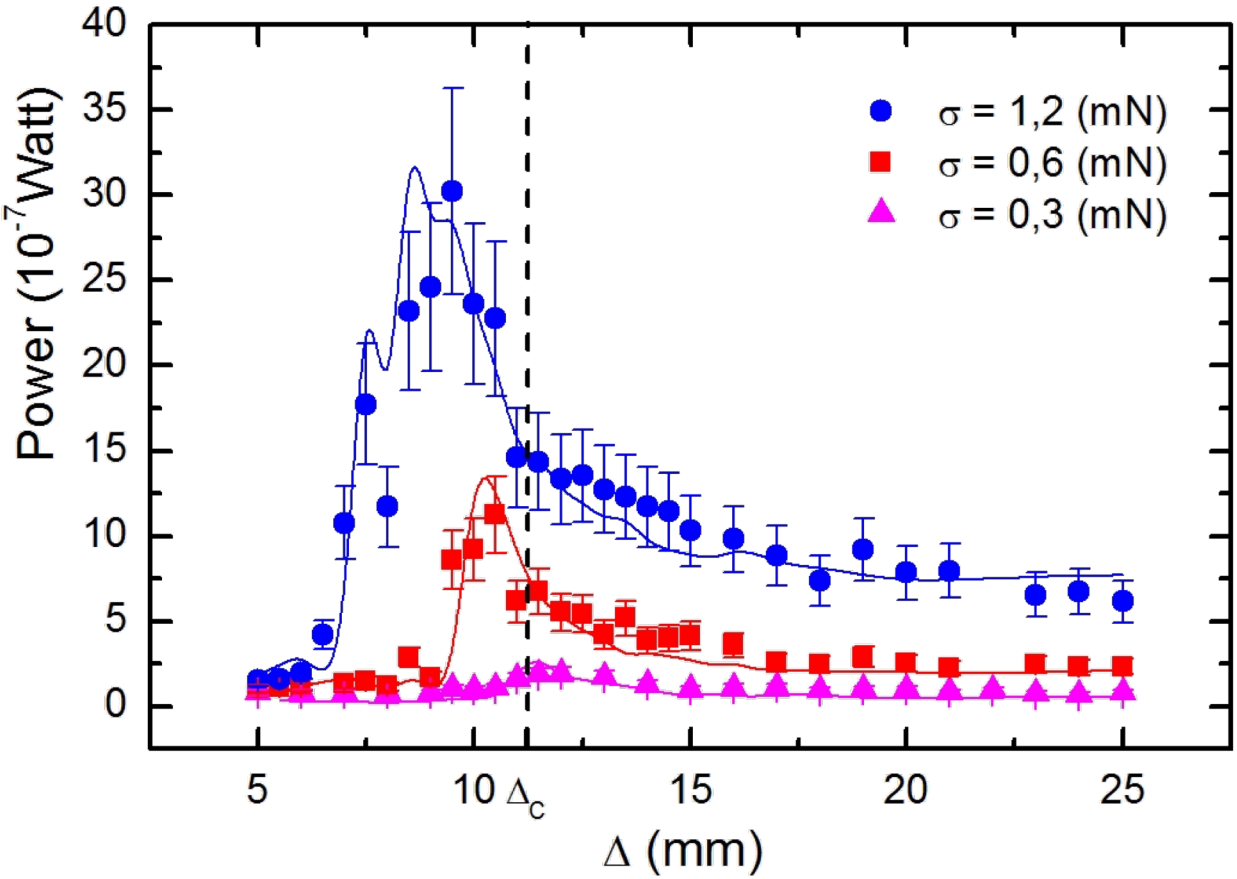


Nonlinear Energy Harvesting, F. Cottone; H. Vocca; L. Gammaitoni, Physical Review Letters, 102, 080601 (2009)

Nonlinear noise harvesting

NON-Linear mechanical oscillators



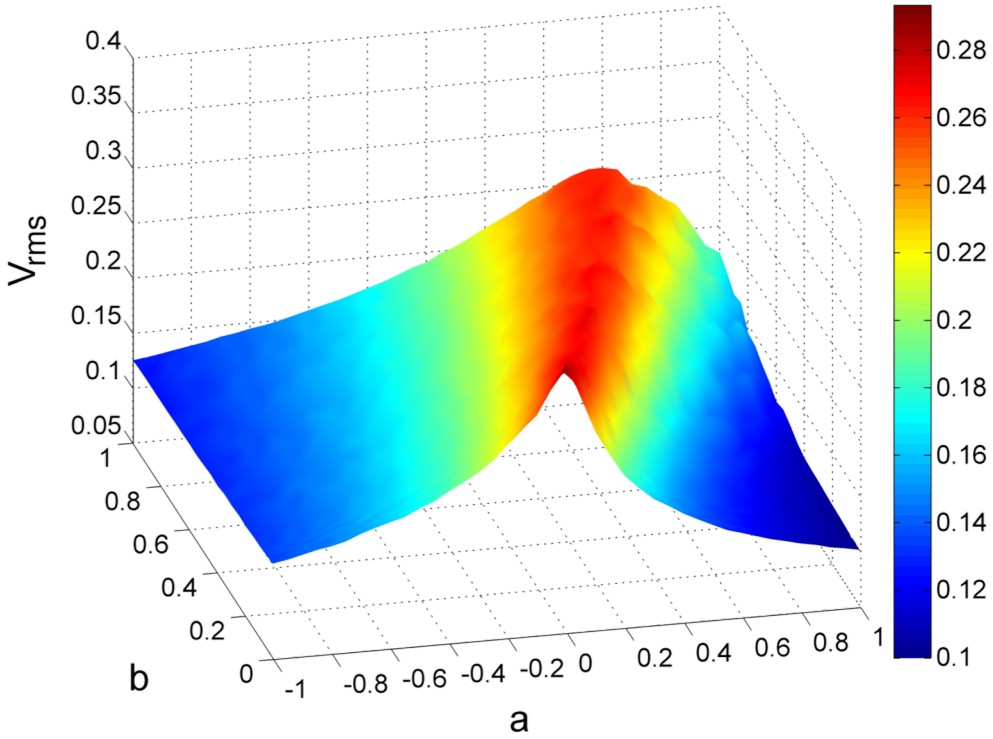


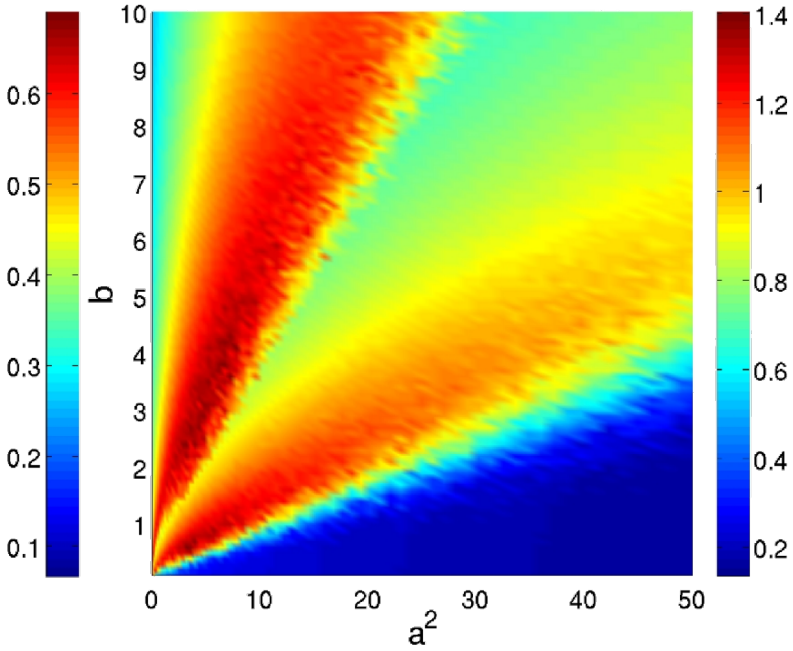
Nonlinear Energy Harvesting, F. Cottone; H. Vocca; L. Gammaitoni , Physical Review Letters, 102, 080601 (2009)

Nonlinear noise harvesting

Duffing potential

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





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

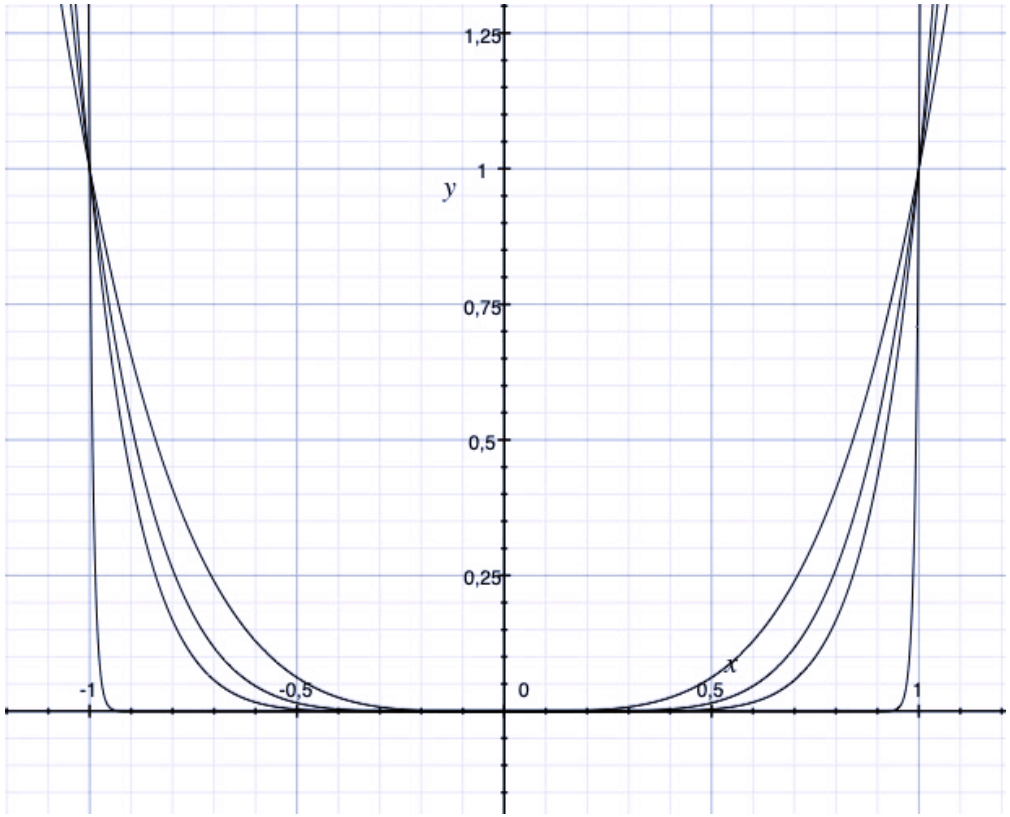
L. Gammaitoni, I. Neri, H. Vocca, Appl. Phys. Lett. 94, 164102 (2009)

Nonlinear noise harvesting

NON-Linear mechanical oscillators

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

$$U(x) = a\, x^4$$
$$U(x) = a\, x^6$$
$$U(x) = a\, x^8$$
$$\dots$$
$$U(x) = a\, x^{2n}$$

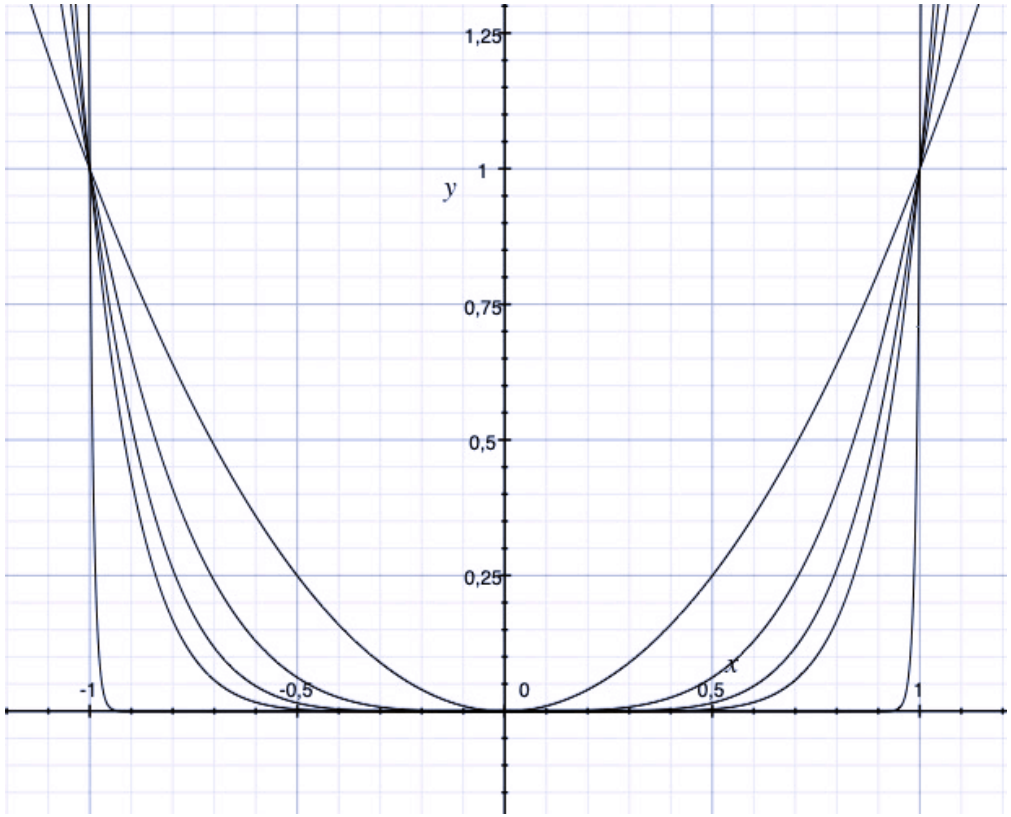


Nonlinear noise harvesting

NON-Linear mechanical oscillators

Comparison with $U(x) = a\,x^2$

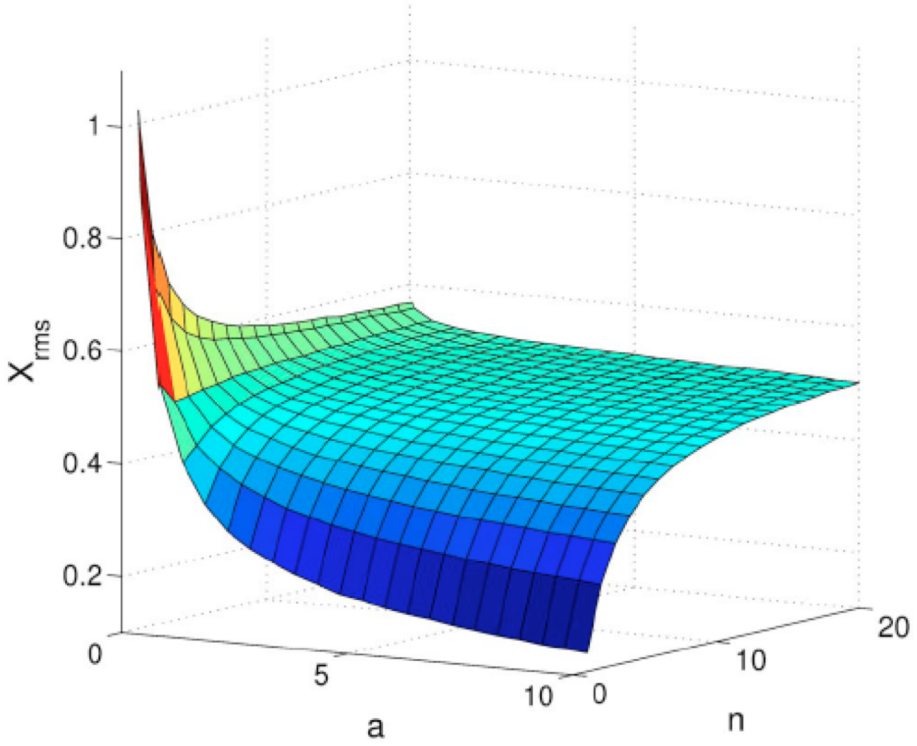
$$U(x) = a\,x^4$$
$$U(x) = a\,x^6$$
$$U(x) = a\,x^8$$
$$\dots$$
$$U(x) = a\,x^{2n}$$



Nonlinear noise harvesting

Monostable potential

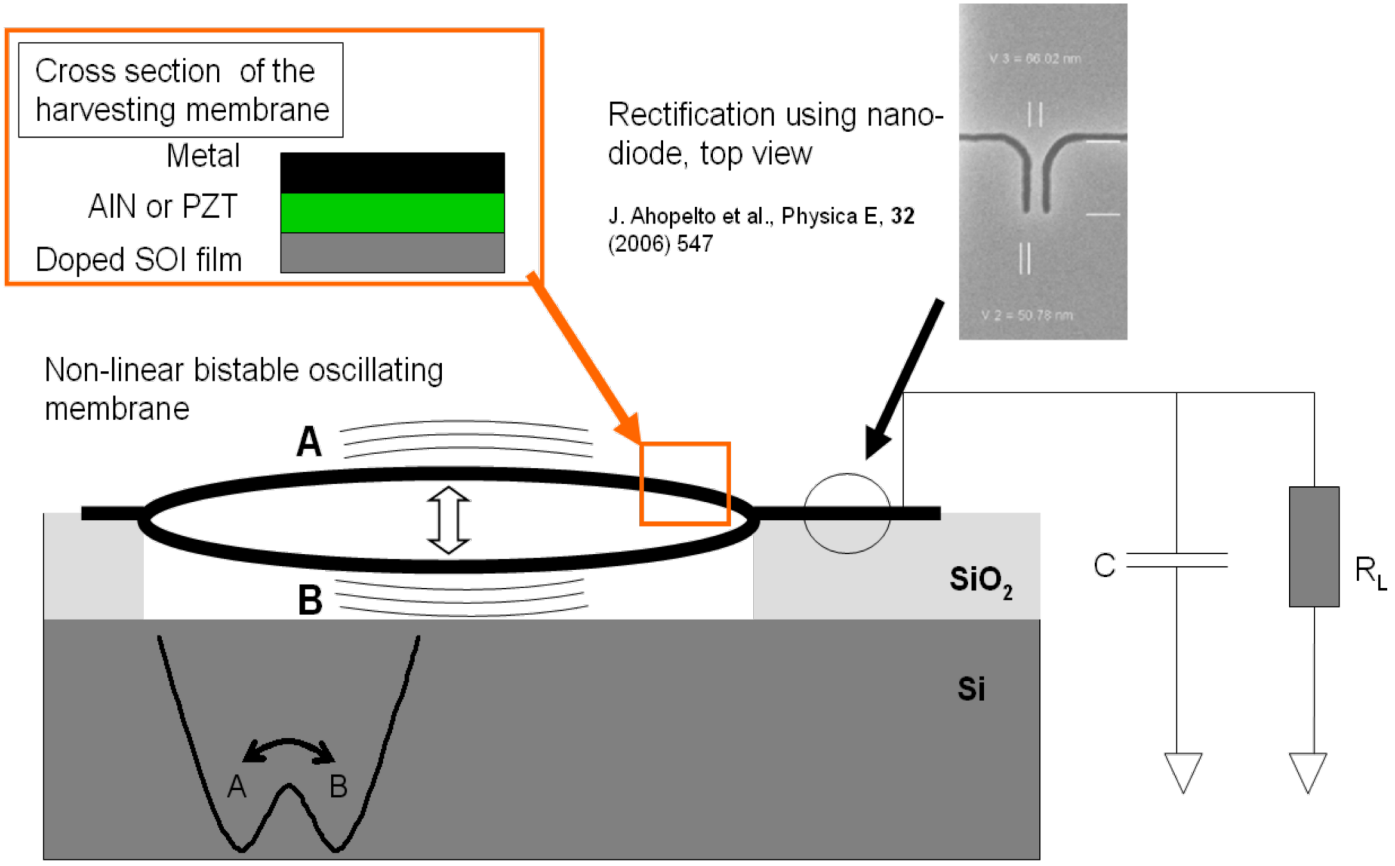
$$U(x) = ax^{2n}$$



Nonlinear oscillators for vibration energy harvesting
L. Gammaitoni, I. Neri, H. Vocca, Appl. Phys. Lett. 94, 164102 (2009)

The benefits of noise and nonlinearity: Extracting energy from random vibrations, Luca Gammaitoni; Igor Neri; Helios Vocca,
Chemical Physics, Volume 375, p.435–438, (2010)

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