Extractable Work in Quantum Electromechanics

Trinity College Dublin
Coláiste na Tríonóide, Baile Átha Cliath
The University of Dublin

QuSys

|T⏲CQS⟩

IRISH RESEARCH COUNCIL
An Chomhairle um Thaighde in Éirinn

Oisín Culhane, Mark Mitchison, John Goold

School of Physics, Trinity College Dublin

Summary

- We model a nano-electromechanical device as a flywheel converting electrical to mechanical work.
- Self sustained oscillations are observed with high bias and energy dependent spectral densities; qualitatively matching recent experiments [1].
- The Ergotropy was found to be a good order parameter for this self sustained oscillation transition.

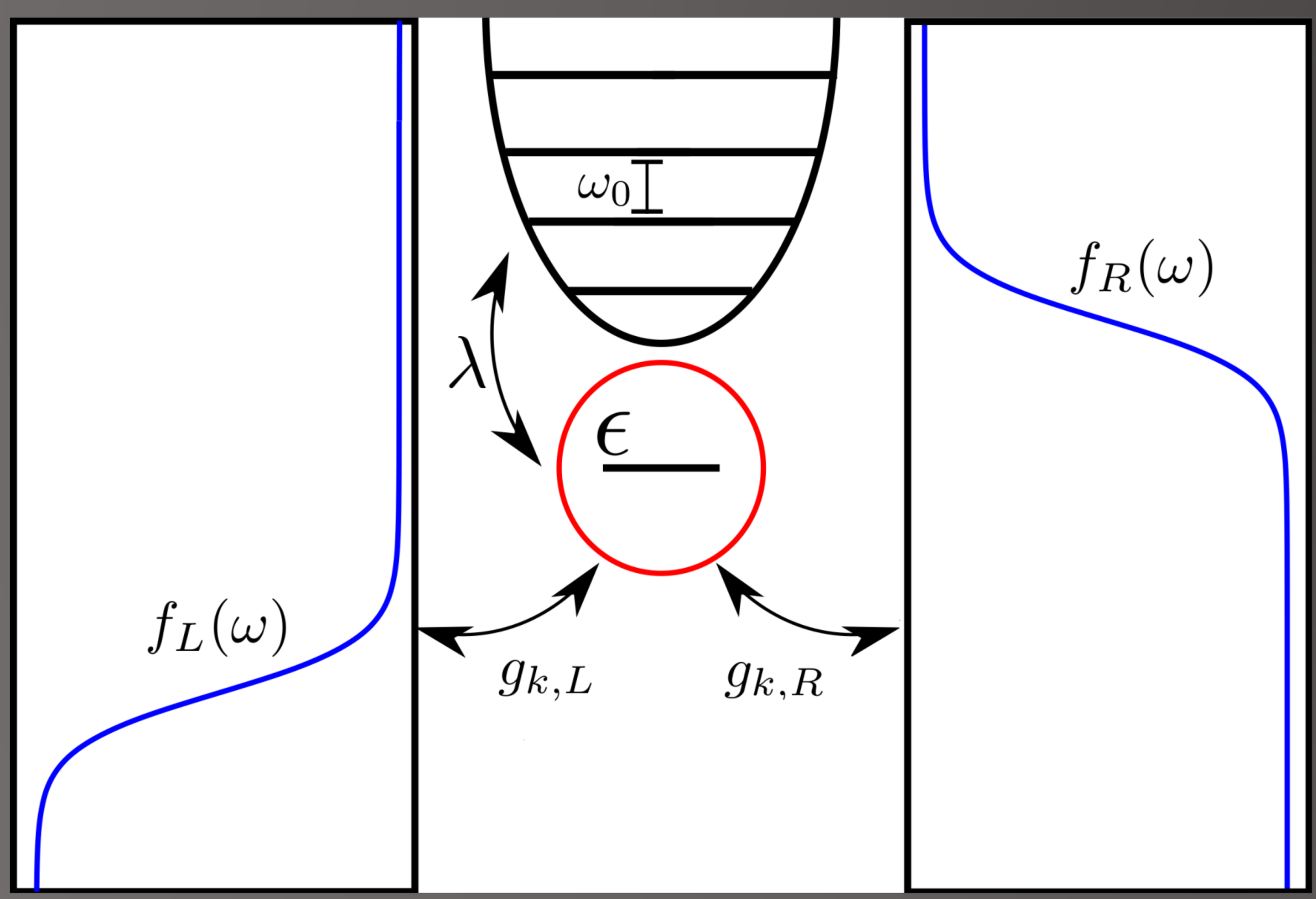

Figure 1: Schematic diagram of a quantum dot is coupled to two electrodes, with temperature T_L and T_R and chemical potential μ_L and μ_R respectively. The quantum dot is also coupled to a harmonic oscillator. The effect of the oscillator is to alter the energy of the quantum dot.

Oscillator Equation of Motion

- System Hamiltonian:

$$\hat{H}_S = \epsilon \hat{c}^\dagger \hat{c}$$

$$\hat{H}_B = \sum_k \left(\Omega_{kL} \hat{d}^\dagger{}_{kL} \hat{d}_{kL} + \Omega_{kR} \hat{d}^\dagger{}_{kR} \hat{d}_{kR}\right)$$

$$\hat{H}_I = \sum_k \left(g_{kL}\left(\hat{c}^\dagger \hat{d}_{kL} + \hat{d}^\dagger{}_{kL} \hat{c}\right) + g_{kR}\left(\hat{c}^\dagger \hat{d}_{kL} + \hat{d}^\dagger{}_{kL} \hat{c}\right)\right)$$

$$\hat{H}_V = \omega_0 \hat{a}^\dagger \hat{a} - F \hat{c}^\dagger \hat{c} \hat{x}$$

- Using the quasi-adiabatic approximation

$$k_B T, \Gamma \gg \omega_0, F$$

- Langevin Equation describing the oscillator

$$m\ddot{x} + m\gamma_x \dot{x} + m\omega_0^2 x = F\langle \hat{n} \rangle_x + \delta F_x(t)$$

- The dissipation and fluctuation terms are given by the noise spectrum

$$D(x) = S_x(0) \qquad \gamma(x) = \frac{1}{m}\frac{dS_x(\omega)}{d\omega}\Big|_{\omega=0}$$

$$S_x(\omega) = F^2 \int_{-\infty}^{\infty} dt\, e^{i\omega t} \langle \delta\hat{n}(t)\delta\hat{n}(0)\rangle_x$$

Steady-State Oscillator

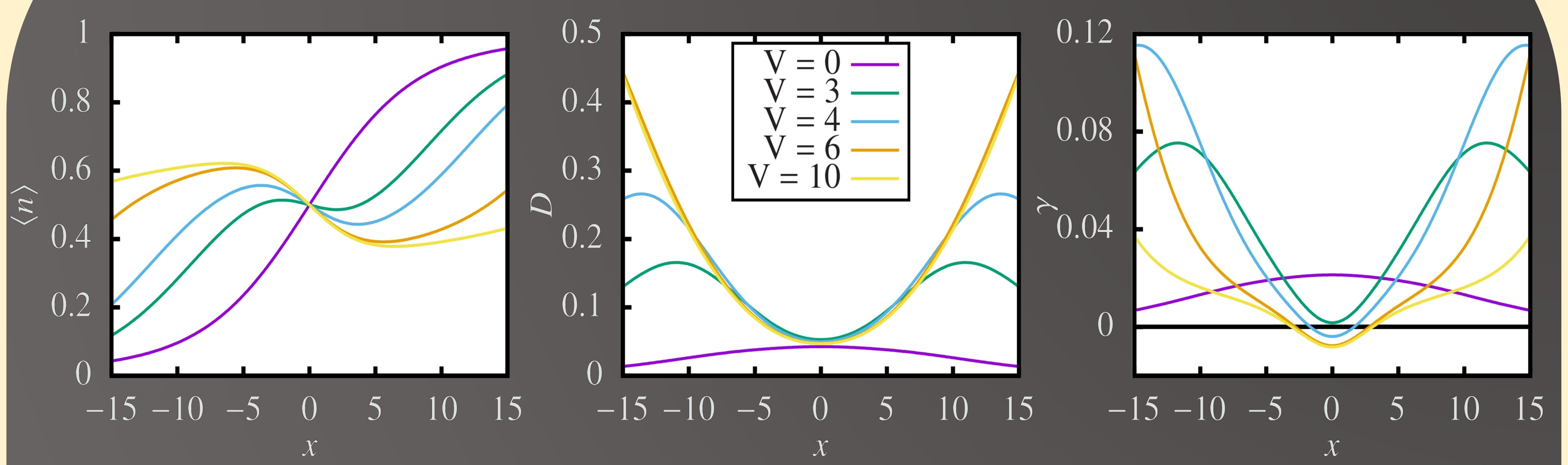

Figure 2: The excess dot occupation, fluctuation and dissipation at various biases. At large bias the damping becomes negative.

- The spectral density is given by a Lorentzian curve

$$\kappa(\omega) = \frac{\Gamma\delta}{(\omega - \omega_\alpha)^2 + \delta^2}$$

- With large applied bias and energy dependent spectral densities one finds negative damping

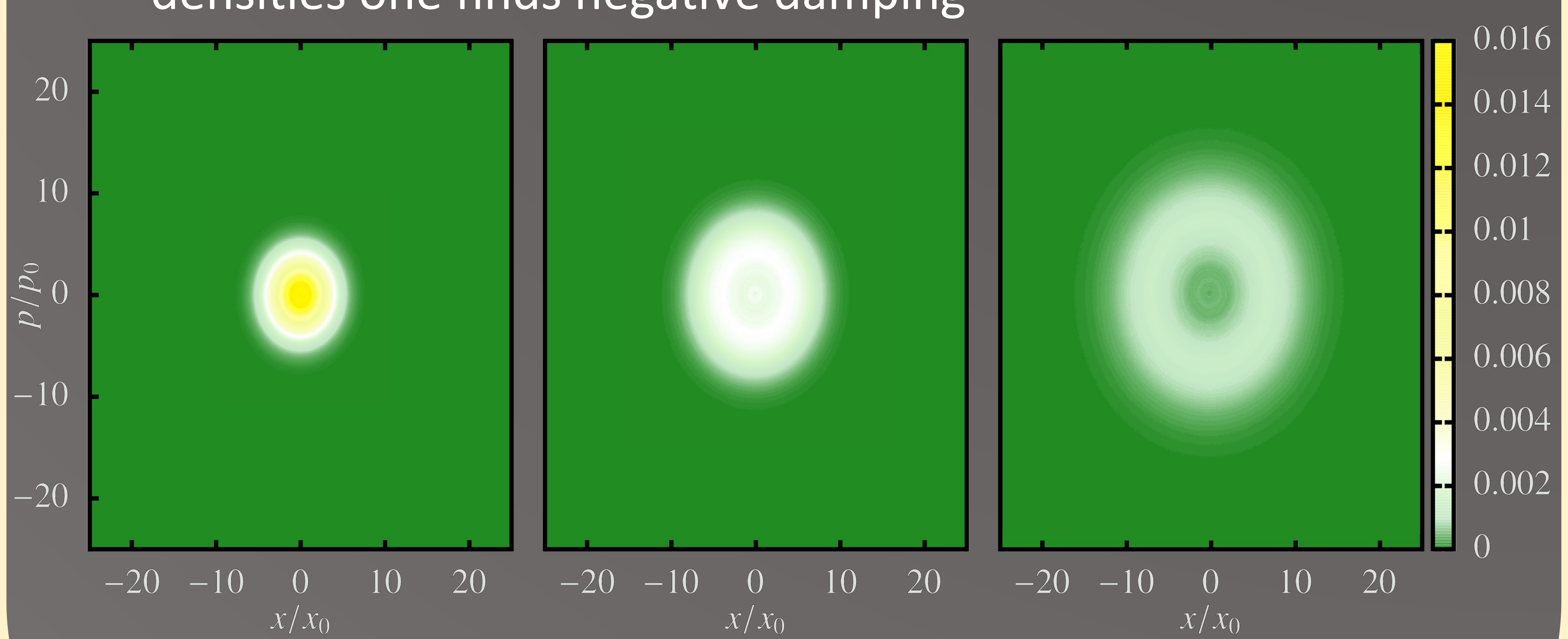

Figure 3: The Wigner Function of the system at various biases. The Wigner function moves from a thermal blob to an annulus shape highlighting the transition to self-sustained oscillations

Ergotropy

- The ergotropy of the oscillator is given by

$$\mathcal{W} = \sum_{j,k} r_j \epsilon_k \left(\left|\langle r_j | \epsilon_k \rangle\right|^2 - \delta_{jk}\right)$$

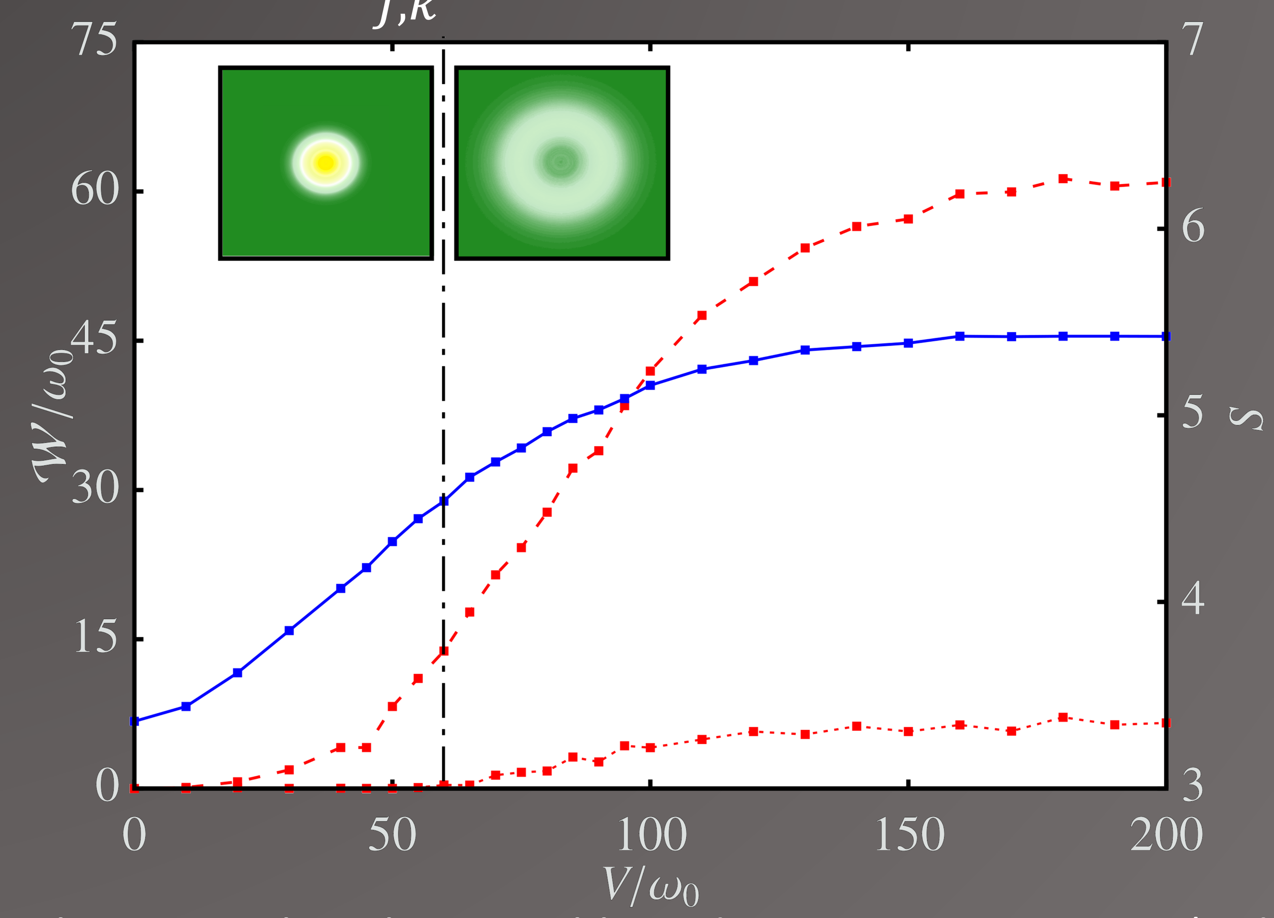

Figure 2: The maximal work extractible under a unitary operation (red, dotted), thermal operation (red, dashed) and the entropy (blue)

Outlook

- Explore the electronic properties of the system – using the self sustained oscillations as a quantum clock.
- Use different systems in the central region of the model.
- Apply a thermal bias and explore the effects of the oscillator.

Further Reading

Culhane O et al arXiv:2201.07819
[1]Wen Y et al Nature Physics 2019; 16:75-82
Clerk A, Bennett S New Journal of Physics 2005;7:238-238
Bennet S, Clerk A, Physical Review B 2016 201301